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Advancing Chemistry Education with 3D Printed Tools

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Advancing Chemistry Education with 3D Printed Tools

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An Interactive Qualifying Project Report
Submitted to the Faculty of the
Worcester Polytechnic Institute
In partial fulfillment of the requirements for the
Bachelor of Science Degree

Approved By:

Abstract

3D printing has proven to be a valuable technological and educational asset. Our project's goal was to incorporate this technology with chemistry education with the hope of allowing chemistry teachers to better teach difficult concepts and topics. With this goal in mind, we conducted surveys with chemistry teachers to determine accessible ways for teachers to incorporate 3D printing tools into chemistry classrooms. Based on the input from teachers, we created a compendium of 3D printable tools, gathered from internet sources, that educators can browse and print. This compendium was available to chemistry teachers from a website on 3D printing and chemistry that we developed: <https://users.wpi.edu/~chem3dprint>. To facilitate teachers' first experiences with 3D printers, we created a beginner's guide that walks a teacher through printing their first object, which is available on our website. In addition, we developed a list of common chemistry misconceptions and difficult topics such as "Identical molecules can vary in size" and "Unbalanced chemical equations exist", as well as provided 3D printable objects, simulations, and lesson plans to help combat and resolve challenges in these topic areas. We compiled all this information on our website for teachers to explore without needing to search the internet for the resources. Additionally, we developed three 3D printable tools to use for chemistry education. The three tools addressed the misconceptions: "identical molecules can vary in size," "breaking bonds releases energy and forming bonds takes energy," "energy is required in both the forming and breaking of chemical bonds," and "there are only 2 types of bonding: ionic and covalent." The 3D printed models we developed were posted to Thingiverse and linked to on our website as solutions to the listed misconceptions. We advanced chemistry education through the creation of our website and tools by bringing together disperse resources into a single, manageable location. Our work will allow more use of 3D printing in chemistry education and help improve chemistry education.

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Table of Contents

Abstract	2
Acknowledgements	3
Table of Contents	4
1. Introduction	7
2. Background	8
2.1 Massachusetts Standards for Chemistry Education	8
2.2 Challenging Chemistry Concepts	9
2.2.1 Matter and its Interactions	10
2.2.2 Motion and Stability: Forces and Interactions	12
2.2.3 Energy	14
2.3 Previous Attempts to Improve Chemistry Education	15
2.4 3D Printing	17
2.4.1 How 3D Printers Work	17
2.4.2 Fused Deposition Modeling	20
2.5 How 3D Printing is used Currently in STEM Education	21
2.5.1 3D Printing Resources for Educators	21
2.5.2 Engineering	22
2.5.3 Biology and Anatomy	23
2.5.4 Chemistry	24
3. Methodology	32
3.1 Information from Chemistry Teachers	33
3.2 Creation of Database of Tools and Lessons	35
3.3 Creation of HTML Compliant Website	36
3.4 Design of Physical Tools to Target Specific Misconceptions	38
4. Results and Discussion	39
4.1 Interviews with WPI Chemistry Faculty	39
4.1.1 Interview with Destin Heilman	39
4.1.2 Interview with Drew Brodeur	40
4.2 Survey of Local High School Chemistry Teachers	43
4.3 Cost Analysis of 3D Printed Molecular Modeling Kit	50
4.3.1 Baseline Molecular Modeling Kit on Amazon	50
4.3.2 Hypothetical 3D Printed Kit Equivalent to Amazon Baseline	51
4.3.3 Cost Effective 3D Printed Molecular Modeling Kit	52

4.4 Cost Analysis of Different 3D Printing Services	53
4.5 Website and Compendium Development	56
4.6 Website Evaluation Survey Results	71
4.6.1 Initial Website Evaluation Survey	71
4.6.2 Second Website Evaluation Survey	71
4.7 Developing 3D Printable Tools for Chemistry Education	82
4.7.1 3D Phases of Water	82
4.7.2 Energy of Bonding	83
4.7.3 Types of Bonds Tool	86
4.7.4 Feedback from WPI Faculty on 3D Printed Tools	89
5. Conclusions and Recommendations	91
5.1 Conclusions and Summary	91
5.2 Future Work and Recommendations	93
Literature Cited	95
Appendices	98
Appendix A: Chemistry Fundamentals	98
Appendix B: Massachusetts Department of Education Physical Science Standards for High School Chemistry	103
Appendix C: Interview Materials	109
Summary of Interview with Professor Destin Heilman	109
Transcript of Interview with Drew Brodeur	110
Appendix D: IRB Approval	115
Appendix E: Survey Distributed to Chemistry Educators and Results	116
Appendix F: Website Evaluation Surveys	119
1. Initial Survey	119
2. Second Survey	125
Appendix G: 3D Printed Modeling Kit Cost Calculations	129
Equivalent Modeling Kit	129
Cost Effective Modeling Kit	129
Appendix H: Additional Website Images	130
Home	130
About	132
3D Printing Guide	133
Contact Us	135
Compendium of Resources	136

List of Common Chemistry Misconceptions and Solutions

138

1. Introduction

3D printing is a relatively new way of creating almost any object you can imagine out of plastic or other materials. This technology is used extensively in commercial enterprises and less so in education. Companies use 3D printing technology to print prototypes of parts, draft 3D floor plans for architects, and even fabricate entire houses. However, numerous barriers to using 3D printers exist, including expense, time, and the need to learn multiple new software programs. Our project aimed to help chemistry teachers take the step to using 3D printing to print objects that could help with their teaching.

Chemistry education is fraught with misconceptions and difficult concepts. Comprehension of many chemistry topics can be difficult because many of the core concepts (e.g. atoms and molecules) cannot be seen with the eye. Some students have trouble understanding and visualizing some of the complex concepts. For example, molecular modeling kits have been created to help students visualize atoms and molecules. However, molecular modeling kits will not solve every problem. Other tools are needed to help students see and understand hard chemistry concepts. 3D printing could benefit chemistry education by allowing teachers to print such objects or tools.

3D printing has made inroads in education, but it still is not common. This could be due to the lack of visibility of 3D printing, its relatively steep learning curve, or its cost. There were some printable chemistry tools online, but they may be difficult to find and access, especially for those unfamiliar with 3D printing. Based on surveys of local Worcester educators to learn about their experiences with 3D printing, our team collected many of these online 3D printing resources of tools into one place to allow educators to be able to browse and access each tool easily. We also created a list of common misconceptions and difficult concepts and provided ways to resolve each of them using 3D printed objects or online simulations. Lastly, we created physical tools that could be 3D printed to assist with resolving misconceptions for which previously tools did not exist.

All of the resources made throughout the project were combined into a website that we designed, which we hosted on WPI's servers at <https://users.wpi.edu/~chem3dprint>. The website contained a database of 3D printable resources for chemistry teachers, a set of common misconceptions with aids to address them, and a 3D printing guide that we made to ease teachers into their first experience with 3D printing. The website was made publicly available, so that chemistry teachers could access it.

Ultimately utilizing 3D printed tools in their classroom may help teachers to better explain difficult topics in chemistry and enhance their students' education. Through the creation of our website and tools, we advanced chemistry education by bringing together disperse resources on 3D printing into a single, manageable location. The large amount of information on our website will allow teachers to more readily start into the world of 3D printing for education and improve their skill sets.

2. Background

The focus of our project is on chemistry education and how 3D printing can benefit educators and students alike in teaching and learning chemistry. This section will begin by discussing the Massachusetts standards for chemistry education. These standards guided our research on assembling a collection of common misconceptions and difficulties students have in chemistry. Furthermore, information about 3D printers and how they are used in today's educational setting is presented. This information will guide the project towards a feasible goal. For reference, we have included in Appendix A, a short summary of basic chemistry concepts.

2.1 Massachusetts Standards for Chemistry Education

The Massachusetts Department of Education publishes a set of educational standards that public institutions must follow in order to ensure students understand the same basic concepts in science. These standards are important for our work because all chemistry teachers in Massachusetts must follow these standards. The topics addressed by these standards determine what topics may be important to this project. Our project aims to develop teaching tools that chemistry teachers will be able to integrate into current chemistry curricula, for the benefit of student learning.

The Massachusetts Physical Science Standards for High School Chemistry¹ are divided into three areas:

1. Matter and its Interactions
2. Motion and Stability: Forces and Interactions
3. Energy

These areas contain broad topics to be covered in a school's curriculum. The full list of standards provided by the Massachusetts Department of Education can be found in Appendix B. In the following sections, some specific difficulties and misconceptions students have regarding these subjects are explored.

¹ 2016 *Massachusetts Science and Technology/Engineering Curriculum Framework* 2016. Massachusetts Department of Elementary and Secondary Education.

2.2 Challenging Chemistry Concepts

An issue in chemistry education is that often students fail to comprehend the basic building blocks of chemistry.² Dr. Mary B. Nakhleh is an expert in the chemistry field and has done research on chemistry education and common misconceptions that students develop while learning chemistry. In a paper published in 1992, Nakhleh states that “[student’s] construction of a chemical concept sometimes differ from the one that the instructor holds and has tried to present.”³ Dr. Nakhleh goes further to state that “many students are not constructing appropriate understandings of fundamental chemical concepts from the very beginning of their studies”⁴ Nakhleh implies that the cause of students generating their own understandings is due to their background, attitudes, abilities, and personal experiences.⁵

J. Dudley Herron and Susan C. Nurrenbern have also attempted to summarize the issues of the field of chemistry education. In their 1999 paper, “Chemistry Education Research: Improving Chemistry Learning,” they highlight the weaknesses of chemistry education, discuss misconceptions students hold, and explore propositions from other studies to improve chemistry education.⁶ They note that misconceptions held by students are a large impediment to them learning new material effectively.

Below, Sections 2.2.1-2.2.3 present 21 misconceptions and challenging chemistry concepts. The sections especially focus on misconceptions or topics that inherently involve geometric properties or use of 3D spatial visualization. These challenging topics are organized based on the three main categories of the Massachusetts Department of Education’s set of standards for the physical sciences: Matter and its Interactions, Motion and Stability: Forces and Interactions, and Energy. Later, Section 2.2.4 summarizes some examples of ways educators have already attempted to improve chemistry education.

² Nakhleh, M. B. (1992). Why some students don't learn chemistry: Chemical misconceptions. *Journal of Chemical Education*, 69(3), 191-196.

³ Ibid

⁴ Ibid

⁵ Ibid

⁶ Herron, J. Dudley and Susan C. Nurrenbern. 1999. "Chemistry Education Research: Improving Chemistry Learning." *Journal of Chemical Education* 76 (10): 1354.

2.2.1 Matter and its Interactions

This section on “Matter and its Interactions” focuses on the molecular and subatomic nature of matter. This includes the use of the periodic table to predict trends, acid-base and redox reactions, equilibria, and stoichiometry. From literature on the subject, echoed in the table below, there are two topics where misconceptions often appear: physical properties and equilibria. Targeting these topics could assist us in creating an educational resource that aims to help teachers resolve many misconceptions.

Table 1. Misconceptions and challenging concepts related to the topic of “Matter and its Interactions.”

Misconception/Challenging Concept	Further Explanation
Misconception: Molecules change size/shape with pressure or temperature changes ⁷	Students think that an increase in pressure will decrease the size of a molecule. If you put an air balloon in a high-pressure environment it shrinks, students see this as the molecules shrinking rather than getting closer.
Misconception: Identical molecules can vary in size ⁸	Similar to the first misconception, students think a change in temperature, pressure, velocity, etc. can change a molecule's size.
Misconception: Molecules in different phases have different weights ⁹	Students think that in order for a substance to go from a liquid to gas, it must weigh less so it can “float”
Misconception: Atomic radii depends solely on number of protons ¹⁰	Students think nucleus size is the only factor of atomic radii, rather than electron repulsion.
Misconception: Unbalanced chemical equations exist. ¹¹	Students lack the general knowledge of stoichiometry and how to balance equations. I.e. they do not recognize “2H ₂ ” as two sets of diatomic Hydrogen atoms, but rather, four singular Hydrogen atoms.
Misconception: When a reaction reaches equilibrium, the system stops reacting. ¹²	Students don't understand the concept of equilibrium.
Difficulty: Students have trouble identifying what is oxidized and reduced in redox reactions. ¹³	Students often mistakenly identify what is oxidized and reduced in a redox reaction. They either say the opposite, or they are unable to identify either one.

⁷ Nakhleh 1992, 191-196.

⁸ Ibid

⁹ Ibid

¹⁰ Ibid

¹¹ Ibid

¹² Ibid

¹³ Brandriet, Alexandra R. and Stacey Lowery Bretz. 2014. "Measuring Meta-Ignorance through the Lens of Confidence: Examining Students' Redox Misconceptions about Oxidation Numbers, Charge, and Electron Transfer." *Chemistry Education Research and Practice* 15 (4): 729-746. doi:10.1039/C4RP00129J.

<p>Misconception: Reactant and product concentrations are equal at equilibrium¹⁴</p>	<p>Students think all equilibrium reactions need to be 1:1 product:reactant. They don't think different ratios are possible. This misconception is believed to stem from students not understanding how coefficients of chemical reactions are related to equilibrium expressions. They also don't understand the dynamic nature of equilibrium.</p>
<p>Difficulty: Determining the effect of Le Chatelier's Principle on equilibrium¹⁵</p>	<p>Students have lots of difficulty identifying how a reaction will behave when the equilibrium is disturbed by changing the reactant concentration, product concentration, temperature, pressure, volume or other factors influencing the reaction. The number of factors to consider makes this a difficult problem for students to understand.</p>
<p>Difficulty: Students have trouble distinguishing between reaction rate and equilibria¹⁶</p>	<p>Students do not grasp the concept that, although a reaction may be in equilibrium, the forward/backward reaction rates are not zero. This difficulty often arises from incomplete or confusing explanations from the instructor.</p>

¹⁴ Nakhleh 1992, 191-196.

¹⁵ Ibid

¹⁶ Ibid

2.2.2 Motion and Stability: Forces and Interactions

This section on “Motion and Stability: Forces and Interactions” focuses on molecular bonds and multi-atomic interactions. This includes covalent, ionic, and hydrogen bonding, polarity, resonance forms, molecular geometry, and electron shells. From literature on the subject, two general topics that have multiple related misconceptions have been found: molecular geometry and electron orbitals. These topics can be further researched to develop an educational resource for teachers to target multiple misconceptions within one idea.

Table 2. Misconceptions and challenging concepts related to “Motion and Stability: Forces and Interactions.”

Misconception/Challenging Concept	Further Explanation
Misconception: Atoms only have 1 stable electron state ¹⁷	Students don't understand that atoms have different stable electron states (i.e. Fe^{2+} and Fe^{3+} are both found in compounds) and they lack understanding of Lewis structures.
Misconception: Ions in solutions are still connected ¹⁸	Students confuse covalent bonding with ionic bonding and think of ionic bonding as one atom donating an electron to another atom, creating a bond in solution. They do not understand that ionic bonding is simply from opposite charges attracting.
Misconception: There are only 2 types of bonding: ionic and covalent ¹⁹	Students do not understand that bonds can be mixed, and that the bond itself depends on electronegativity between the atoms in question.
Difficulty: The effect of different bond types (e.g. double, triple bonds) on shape ²⁰	Students have trouble understanding how double and triple bonds affect shape of molecules.
Difficulty: 2D to 3D representation of molecules ²¹	Representations of molecules on paper, such as Lewis structures, don't often convey clearly what the molecule's 3D structure will look like. This leads to mistaken ideas about how molecules are actually shaped, because students cannot adequately visualize them.
Difficulty: Identifying isomers ²²	Students cannot identify that two molecules with different structures are isomers if they have the same chemical formula.

¹⁷ Ibid

¹⁸ "Chemical Misconceptions I - Chemical Bonding." 2008. *Royal Society of Chemistry* 4.

¹⁹ Ibid

²⁰ Nakhleh 1992, 191-196.

²¹ Wu, Hsin-Kai and Priti Shah. 2004. "Exploring Visuospatial Thinking in Chemistry Learning." *Science Education* 88 (3): 465-492.

²² Ibid

Misconception: Isomers have different chemical formulas ²³	Students think that two molecules with the same chemical formula, but different structures (isomers) have different chemical formulas due to their different shapes. They do not understand that the chemical formula only shows the amount of each type of element in the molecule.
Difficulty: How VSEPR predicts bond shape/angles ²⁴	Students who have trouble visualizing motion and shapes of molecules in 3D space have trouble applying VSEPR to problems of molecular shape. Therefore, students don't know when or how to use VSEPR and have trouble understanding bond angles and why molecules form the shapes they do.
Difficulty: How Lewis diagram relates to VSEPR ²⁵	Students don't understand electron orbitals and how they relate to molecular geometry.

²³ Ibid

²⁴ Nakhleh 1992, 191-196.

²⁵ Ibid

2.2.3 Energy

This section on “Energy” focuses on energy balances in chemical processes. This includes endothermic and exothermic relationships, and loss or gain of energy when breaking and forming bonds. Both of the topics are misconceptions, rather than just general challenging concepts. The misconceptions, however, that do appear frequently, are related to reactions.

Table 3. Misconceptions and challenging concepts related to “Energy.”

Misconception/Challenging Concept	Further Explanation
Misconception: Energy is required in both the forming and breaking of chemical bonds	Students do not understand when energy is input to a system during the formation of chemical bonds. “some [students] believe that energy is required in both bond formation and bond breaking.” ²⁶
Misconception: Breaking bonds releases energy and forming bonds takes energy	Students mistakenly relate breaking to releasing of energy and forming to creation of energy. “[S]ome of the students in both groups believe that bond formation needs energy while bond breaking releases energy” ²⁷

²⁶ Özmen, Haluk, Hülya Demircioğlu, and Gökhan Demircioğlu. 2009. "The Effects of Conceptual Change Texts Accompanied with Animations on Overcoming 11th Grade Students' Alternative Conceptions of Chemical Bonding." *Computers & Education* 52 (3): 681-695. doi:10.1016/j.compedu.2008.11.017.

²⁷ Ibid

2.3 Previous Attempts to Improve Chemistry Education

Chemistry educators have tried many ways to improve chemistry teaching. Table 5 shows a sampling of strategies discussed in the literature. Many attempts to help students understand chemistry concepts involve visualization tools such as computer animation and physical models. Other attempts focus on increased exposure to labs and activities to provide students with more hands-on experience to understand classroom material. Additional attempts have identified the issue to be with the structure of teaching the material and have tried to change the way teachers teach chemistry. Table 4 outlines some strategies that educators have used to improve chemistry education.

Table 4. Sample strategies educators have used to attempt to address students' misconceptions and learning difficulties. In the left column is a short description of the strategy. The right column has more details of the strategy.

Strategy	Strategy Details
Analogies and Physical Models	Teachers often use physical models in class and try to make certain ideas easier to understand using analogies. These are common tactics; however, they can only be effective if the relationship between the analogy/model and the actual phenomenon is well understood. ²⁸
Computer Animations	Teachers have also tried using computer animations to display reactions to give students a better understanding of what is happening physically on the molecular level. ²⁹
Increasing Amount of Lab Activities	Including more lab activities to supplement lectures could help students understand material better by giving them more hands-on experience with chemistry rather than abstract lectures. ³⁰
Virtual Lab Activities	One way to include more labs in a chemistry class would be to use virtual lab activities on in-class computers. This is safer, cheaper, and more time effective than traditional labs, and are "at least as effective" as physical labs. ³¹
Reordering the Curriculum	The traditional ordering of class topics is not as intuitive for students as it is for teachers and professors. Reordering the curriculum so it flowed more easily could make it easier for students to learn concepts. ³²
Conceptual Challenges	Educators challenge students' misconceptions by presenting them with situations and evidence that demonstrate their preconceived thoughts were wrong so they can change their own way of thinking. ³³

Model kits are one example of a physical representation used to help teach certain topics in chemistry. Physical models like this can help students visualize atom-scopic concepts at the hands-on level. Traditionally these models come from education companies which produce the models. With the spread of affordable 3D printers in the last decade, educators now possess the opportunity to make their own models, in their own classroom.

²⁸Gabel, Dorothy. 1999. "Improving Teaching and Learning through Chemistry Education Research: A Look to the Future." *Journal of Chemical Education* 76 (4): 548.

²⁹ Özmen et al. 2009, 681-695.

³⁰ Gabel 1999, 548.

³¹ Tatli, Zeynep and Alipasa Ayas. 2013. "Effect of a Virtual Chemistry Laboratory on Students' Achievement." *Journal of Educational Technology & Society* 16 (1): 159-170.

³² Cooper, Melanie and Michael Klymkowsky. 2013. "Chemistry, Life, the Universe and Everything: A New Approach to General Chemistry, and a Model for Curriculum Reform." *Journal of Chemical Education* 90 (9): 1116-1122.

³³ Özmen et al. 2009, 681-695.

2.4 3D Printing

3D printing was first developed in 1981 as a way to create objects by depositing materials in layers to build a full 3D object, also known as additive manufacturing.³⁴ Since then, 3D printing has grown dramatically in use. It is used for instance in healthcare, aerospace, cooking, art, clothing, automotives, construction, weapon design and many more fields too numerous to list. The applications within those fields are just as numerous: 3D printers have made functioning heart valves out of living tissue; 3D printers can make perfect, edible 3D sculptures on the tops of cakes; 3D printers have printed entire houses and bridges safe for people to use. The materials used in 3D printers are just as varied. Nylons, Acrylonitrile-Butadiene-Styrene (ABS), biodegradable polylactic acid (PLA), flexible polymers, glow-in-the-dark plastics, wax, ceramics, and even metals such as bronze and tin³⁵ can be printed on a run-of-the-mill Fused Deposition Modeling printer, the most common type of 3D printer.

2.4.1 How 3D Printers Work

There are many types of 3D printers, but all of them work off of the same basic principle of creating a three-dimensional object by making it layer by layer. Each layer is made to a desired thickness and infill percentage (percentage of plastic inside the object), and then the layers are fused, one on top of the other, to form a full 3D shape from the 2D layers. Figure 1 shows the process from idea to final printed object.

³⁴ Goldberg, Dana. "History of 3D Printing: It's Older than You Think." *Redshift*, accessed Oct 7, 2017.

³⁵ "The Virtual Foundry" *.thevirtualfoundry.com*, accessed Oct 10, 2017.

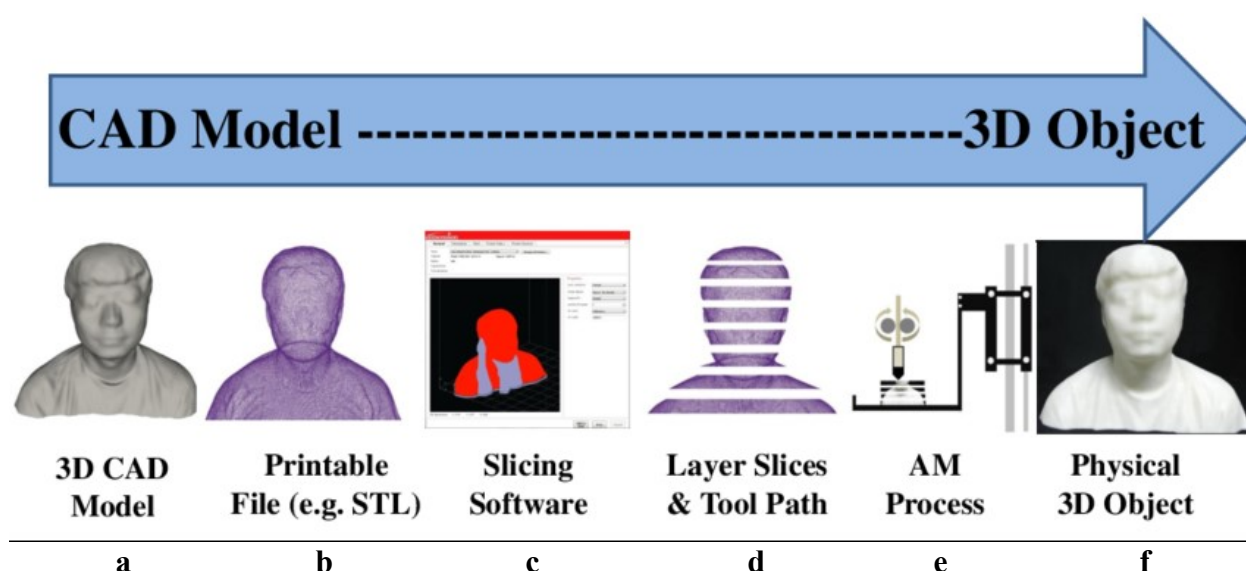


Figure 1. 3D Printing Process. <https://www.researchgate.net> under [CC BY 2.0 by Creative Commons](#). From left to right, a). A 3D CAD model is created by a user or downloaded from the internet. b). The CAD model is converted into an STL file, typically by the CAD software.³⁶ c). The STL file is opened in a slicing software which configures print settings. d). The slicing software “slices” the object into layers and uploads inputted settings into a format the printer can read. e). The printer then prints the object using the inputted settings.³⁷ f). An object is created in 3D space via 3D printing.

In order to 3D print an object, there first must be a virtual 3D representation of the object in a digital file as shown in Figure 1 (left side). To create the 3D object representation, Computer Aided Design (CAD) software is used to create a digital object. While hundreds of 3D object formats exist, the most common format used in 3D printing is the STL file. Most CAD programs are able to export the 3D object in the STL format.³⁸ While the STL file is the 3D object format understood by most 3D printers, it still isn't the final form of the file needed to 3D print an object; the STL file still needs to be sliced into the individual layers that will compose the final object as seen in Figure 2. Slicing is either done by the user before printing, or by the printer before it prints. Once the object has been digitally sliced into layers, it is ready to be printed.³⁹

³⁶ Chakravorty, Dibya. "STL File Format for 3D Printing - Simply Explained." *All3DP*, accessed Oct 7, 2017.

³⁷ "What is 3D Printing?" *3DPrinting.com.*, accessed Oct 8, 2017.

³⁸ Chakravorty, Dibya. "STL File Format for 3D Printing - Simply Explained." *All3DP*, accessed Oct 7, 2017.

³⁹ "What is 3D Printing?" *3DPrinting.com.*, accessed Oct 8, 2017.

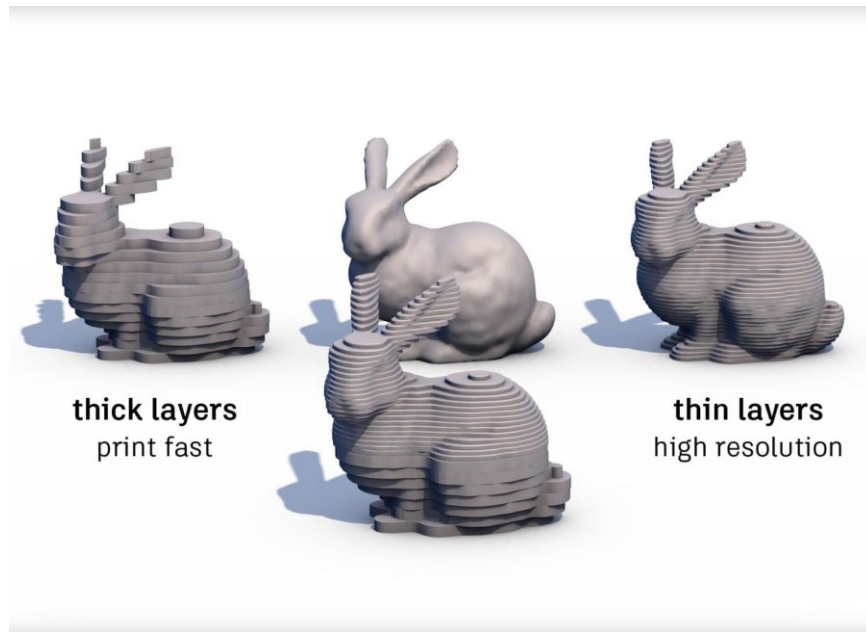


Figure 2. Slicing software will slice a part into layers. Different layer thicknesses affect object quality and print speed, as are shown for the same object. <http://www.fabbaloo.com> under [CC BY 2.0 by Creative Commons](#)

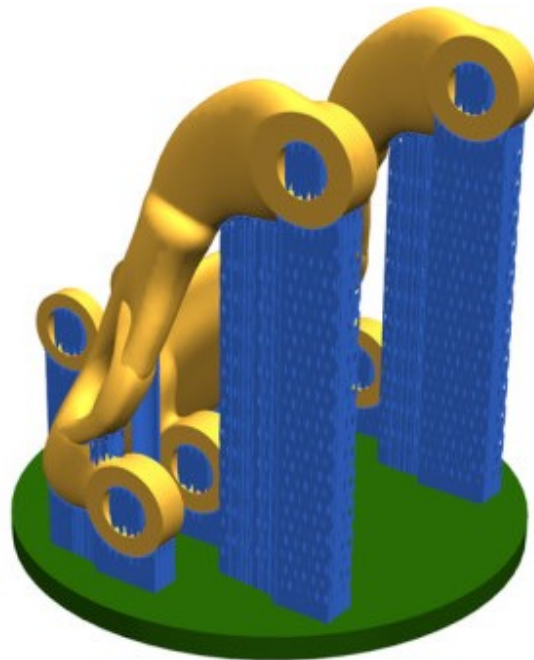


Figure 3. While printing, a 3D printer will create supports (blue) to stabilize the part (yellow) in order to make sure the part does not sag or droop. <http://www.fabbaloo.com> under [CC BY 2.0 by Creative Commons](#)

Depending on the technology of the printer used, overhangs and holes in vertical walls of a part can be a problem. The slicing software sometimes has to modify the object to be printed to

ensure that the final object is printable. For instance, when there is no material underneath to support a layer of an overhang or top of a hole as they are printed, that layer will often droop and could break. To combat this, the slicing software will add thin vertical material underneath overhangs and holes called support material as shown by the blue material in Figure 3.⁴⁰ The support material prevents drooping during the print and is designed to be easily broken off by hand once the print is finished. Another common modification the slicing software may add are features called rafts. Rafts are interface layers made between the object and the initial surface the object is printed on. Rafts help the print adhere to the printing surface so the part does not warp or bend as it is printed, as shown by the green material in Figure 3. Some slicing programs may employ additional techniques to enhance the printability of the printed object, but these are the techniques common amongst all 3D printers.

2.4.2 Fused Deposition Modeling

Fused Deposition Modeling (FDM) is one of the common printer types found in educational settings. An FDM printer extrudes a thin bead of hot, melted plastic out of the extruders tip. The printer moves the extruder in 3D space to lay down beads of plastic to slowly build up the object as shown in Figure 4.

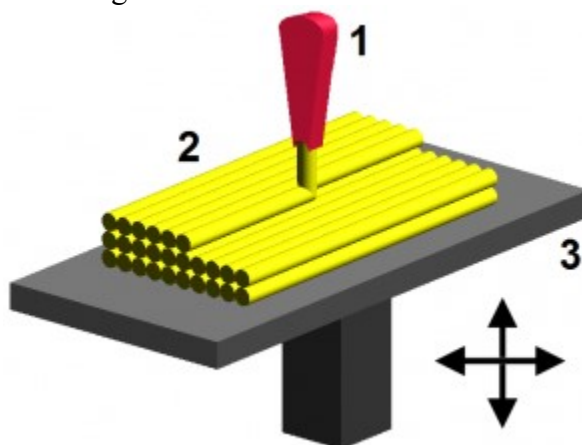


Figure 4. FDM Printer Operation. <http://3dinsider.com> under [CC BY 2.0 by Creative Commons](#). As shown: 1). The extruding nozzle, 2). Plastic placed by the extruding nozzle in layers, 3). Heated printing bed which holds the plastic. The nozzle travels back and forth placing molten plastic which rapidly cools and solidifies.

Because the extruder head has to travel a long distance to make a part, going back and forth over the object, the process is quite lengthy, usually measured in hours. FDM printers are usually fairly simple machines that are commonly targeted at low volume, low quality parts. Its ideal use is creating individual unique parts or making small batches of parts. Due to the simplicity and lower quality of the parts produced by FDM printers compared to other types of 3D printers, they are the cheapest type of 3D printer on the market.⁴¹ Because of their simplicity, however, they are very easy to get up and running with minimal training. In educational settings, FDM printers usually range in cost from \$800-\$2000.

⁴⁰ "What is 3D Printing?" *3DPrinting.com.*, accessed Oct 8, 2017.

⁴¹ Locker, Anatol. "9 Basic Types of 3D Printers - 3D Printing Technology Guide." *All3DP*, accessed Oct 8, 2017.

2.5 How 3D Printing is used Currently in STEM Education

Schools and educators are seeking ways to incorporate 3D printing into their curricula to prepare students for the future. Individual teachers and departments are buying 3D printers to design and create new, creative tools for education. Besides teachers and schools, some industries are helping improve the accessibility of 3D printing. As these industries (aerospace, robotics, medical, etc.) have begun to use 3D printers, companies in those industries have offered incentives and grants to schools help the schools purchase and use 3D printers in their curricula.⁴² Despite the increase of 3D printing in the classroom, we found no quantitative research determining if 3D printed tools are effective in improving students' understanding of difficult topics. In spite of this, the number of tools available for STEM education are numerous.

2.5.1 3D Printing Resources for Educators

Educators already have several 3D printing resources available to them. There are communities to help educators develop, share, and use 3D printing in their everyday lessons, such as Thingiverse Education. Thingiverse Education builds off of the existing Thingiverse site, which allows users and educators to publish STL files for objects to print, along with pictures of the finished 3D printed part. Thingiverse Education builds upon this foundation by providing lesson plans and materials along with the 3D printing part files for every subject taught in schools, to guide teachers through printing and incorporating the parts in their lessons. These lessons on Thingiverse Education walk a teacher through the steps to successfully print the parts and incorporate them into lesson plans.⁴³

Thingiverse Education has a large mix of lesson plans and objects for topics such as art, history, music, science, technology, and engineering. The majority of the objects are within the “technology” and “engineering” categories. Within the “science” category, the chemistry section has dozens of tools for chemistry education, such as parts to make inexpensive centrifuges, molecular modeling kits, and printed electron orbitals. On 3D printing websites like Thingiverse, if a part or lesson plan doesn't exist for a particular topic, anyone can design the part and lesson plan, and then upload instructions and part files for anyone else to use.

Beyond Thingiverse Education, other 3D printing companies have similar sites available for educators. Stratasys, one of the largest 3D printer makers and owner of the popular 3D printer company Makerbot, has created entire curriculum guides for integrating 3D printing into kindergarten through university education.⁴⁴ Shapeways, one of many companies that will print STL part files you submit to them online, has special programs for educators and students to provide them assistance in 3D printing. Shapeways gives educators and students reduced cost printing opportunities as well as the ability to apply for grants for free 3D printing using their service.⁴⁵ Some of the applications and lessons from these 3D printing resources and other sources are described below.

⁴² “Vandegrift ViperBots Robotics Organization.” *Viperbots.org*, accessed Oct 8, 2017.

⁴³ “Thingiverse Education.” *Thingiverse*, accessed Oct 8, 2017.

⁴⁴ “Stratasys|3D Printing and Resources for Education.” *Stratasys*, accessed Oct 8, 2017.

⁴⁵ “Shapeways EDU Program - Shapeways.” *Shapeways.com*, accessed Oct 8, 2017.

2.5.2 Engineering

3D printing is already commonly used in industry, and many engineering and technology classes utilize or teach about 3D printing. In experimental engineering classes, 3D printing can be used to create lab equipment for the students to customize and use. Common equipment includes levers, pulleys, and masses to enhance the labs and help students perform experiments, understand concepts better, and have a more enjoyable experience.⁴⁶ Examples of some 3D printed pulleys for an engineering class is shown in Figure 5.



Figure 5. 3D printed pulleys for use in physics classes. www.thingiverse.com⁴⁷ by [Moko](#) under [CC BY 2.0 by Creative Commons](#)

In other engineering classes, 3D printers are used to help students test their designs. For example, in a statics class, after designing a bridge for a project, the students will actually print out their bridge design and see how well it actually performs.⁴⁸ 3D printing is also used heavily in robotics classes. As just one of many examples, some robotics classes are using 3D printers to give students access to cheap robotics parts they can use to have hands on experience for learning programming.⁴⁹ Many larger robotics programs and classes, such as those for FIRST Robotics, have incorporated 3D printing into their curriculum. Beyond just using 3D printed objects, the students learn how to design and produce their own 3D printed parts to use on their robots.⁵⁰

⁴⁶ "MOKO Mini Pulley by Moko." *Thingiverse*, accessed Oct 8, 2017.

⁴⁷ <https://www.thingiverse.com/thing:153197>

⁴⁸ "Bridge Builders." *Thingiverse*, accessed Oct 8, 2017.

⁴⁹ Gonzalez-Gomez, J., A. Valero-Gomez, A. Prieto-Moreno, and M. Abderrahim. 2012. "A New Open Source 3D-Printable Mobile Robotic Platform for Education." In *Advances in Autonomous Mini Robots: Proceedings of the 6-Th AMiRE Symposium*, edited by Ulrich Rückert, Sitte Joaquin and Werner Felix, 49-62. Berlin, Heidelberg: Springer Berlin Heidelberg.

⁵⁰ "Vandegrift ViperBots Robotics Organization." *Viperbots.org*, accessed Oct 8, 2017.

2.5.3 Biology and Anatomy



Figure 6. 3D printed cell for biology education. www.thingiverse.com by [MosaicManufacturing](#) under [CC BY 2.0 by Creative Commons](#)

3D printing has also been used in biology and anatomy classes. For instance, instead of chalkboard models and posters of cells, biology teachers can print models of cells out in different colors so their students are more engaged.⁵¹ A sample 3D printable cell model is shown in Figure 6 above. 3D models help students visualize how cells are structured and help eliminate some of the conceptual difficulty with how the various components in a cell interact. Using 3D printing, biology teachers have also been able to create 3D models of ATP synthase to demonstrate to students how cells make energy.⁵² Beyond just cellular biology, the anatomical biology uses of 3D printing are endless. Instead of the costly process of dissecting corpses to allow students hands on experience with how biological systems work, educators can 3D print the organs, bones and structures they want the students to learn about from 3D CT scans of a cadaver, and printing multiple copies allow all students to have a common basis to work from.⁵³ ⁵⁴ 3D printing helps reduce the cost and difficulty of running labs, providing students access to more experiments.

⁵¹ "Multi-Color Cell Model by Mosaic Manufacturing." *Thingiverse*, accessed Oct 8, 2017.

⁵² "ATP Synthase." *Thingiverse*, accessed Oct 8, 2017.

⁵³ AbouHashem, Yousef, Manisha Dayal, Stephane Savanah, and Goran Štrkalj. 2015. "The Application of 3D Printing in Anatomy Education." *Medical Education Online* 20 (1): 29847-3.

⁵⁴ McMenamin, Paul G., Michelle R. Quayle, Colin R. McHenry, and Justin W. Adams. 2014. "The Production of Anatomical Teaching Resources using Three-dimensional (3D) Printing Technology." *Anatomical Sciences Education* 7 (6): 479-486.

2.5.4 Chemistry

3D printing is also used in chemistry education. A common use of 3D printing in chemistry has been to print representations of electron orbitals as seen in the second row of Table 5. These models focus on showing the orbital shapes of electron separately from the atom.^{55 56} With advances in software, it is now possible to completely model any molecule inside of specific software packages. As seen in the top of Figure 7, a model is drawn out in 2D space and then transferred into a 3D model in the same software. These models can then be exported into a file that 3D printers can read and print. The bottom half of Figure 7 shows the same molecular model converted into the STL file a 3D printer can understand.

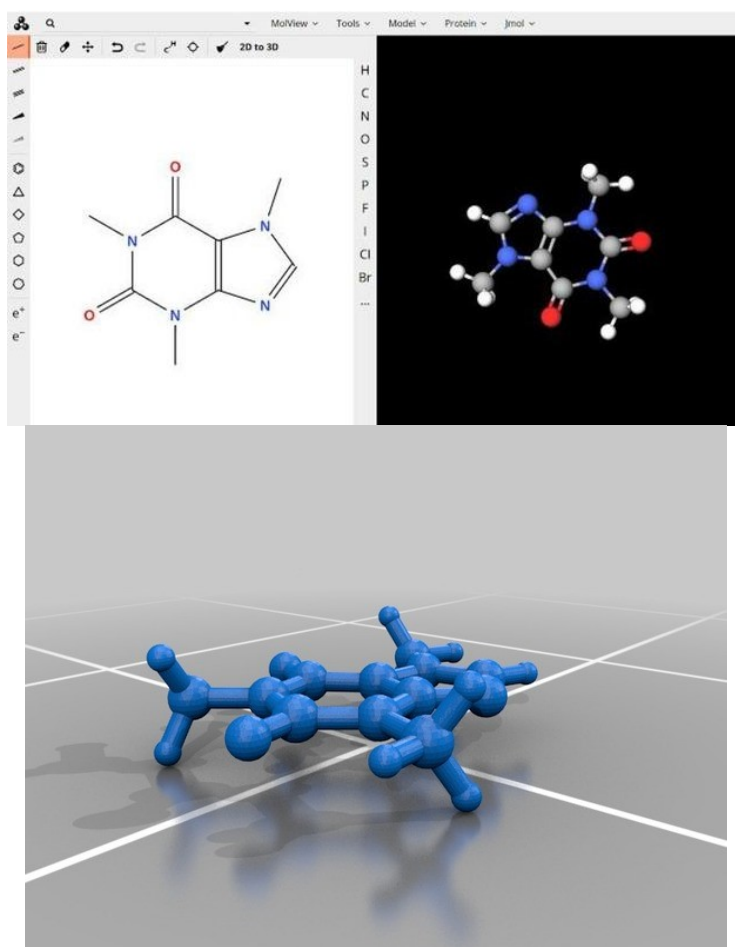


Figure 7. Converting molecule drawing to a 3D model to print in MolView, and the model converted to an object file. www.thingiverse.com by [ryan74](#) under [CC BY 2.0 by Creative Commons](#)

⁵⁵ Griffith, Kaitlyn M., Riccardo De Cataldo, and Keir H. Fogarty. 2016. "Do-it-Yourself: 3D Models of Hydrogenic Orbitals through 3D Printing." *Journal of Chemical Education* 93 (9): 1586.

⁵⁶ "Atomic Orbital Collection." *Thingiverse*, accessed Oct 8, 2017.

Another common use of 3D printing in chemistry education is 3D printing entire molecules or crystal structures. This allows students to visualize the actual structures of the molecules and compounds they are working with. There are many examples of this particular approach to using 3D printing in chemistry. In some universities, chemistry educators are using 3D printing to create entire surfaces of protein structures to help their students visualize how proteins interact with each other.⁵⁷ In material science and chemistry classes at other universities, teachers have 3D printed crystallographic unit cells to give students a more intuitive grasp of what crystal structures look like and how that impacts the strength of the material the structures form.⁵⁸ Another way teachers are bringing full molecules into the classroom is by using 3D ball and stick model files of molecules, and then converting them into printable STL files using programs such as Chimera.⁵⁹ Chimera is the only program that converts the scientific molecule formats into printable STL files. The process and results of such a conversion are shown in Figure 7. The teachers have many sources to help create the full molecules. They can either use programs that export the physical molecules properties, such as MolView,⁶⁰ or they can find common premade molecules, structures and compounds in a database such as the National Institute of Health's 3D print exchange to create molecules like those in rows 3 and 5 of Table 5.⁶¹

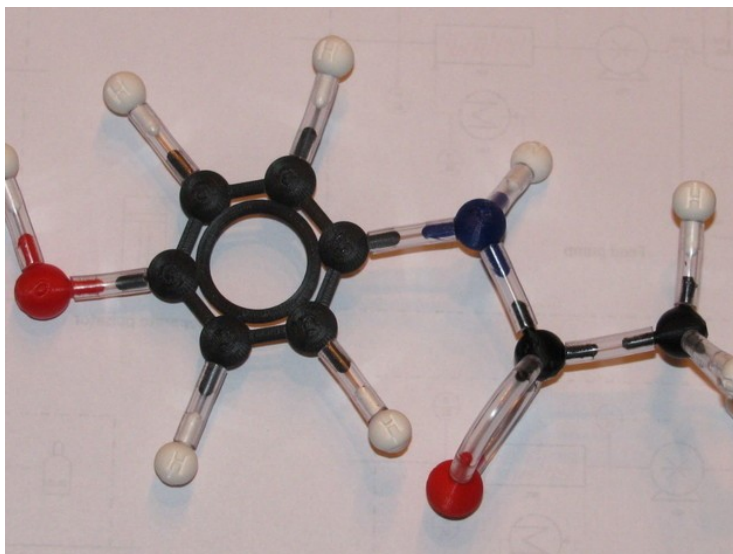


Figure 8. Acetaminophen molecule made with 3D printed molecular modeling kit.
www.thingiverse.com by [betawolf](#) under [CC BY 2.0 by Creative Commons](#)

3D printing has also been used to make many of the common tools in chemistry education, namely molecular building kits, more easily accessible and customizable for teachers.

⁵⁷ Meyer, Scott C. 2015. "3D Printing of Protein Models in an Undergraduate Laboratory: Leucine Zippers." *Journal of Chemical Education* 92 (12): 2120.

⁵⁸ Rodenbough, Philip P., William B. Vanti, and Siu-Wai Chan. 2015. "3D-Printing Crystallographic Cells for Learning Materials Science and Engineering." *Journal of Chemical Education* 92 (11): 1960.

⁵⁹ Chimera: <https://www.cgl.ucsf.edu/chimera/>

⁶⁰ "Chemical Modeling." *Thingiverse*, accessed Oct 8, 2017.

⁶¹ "NIH 3D Print Exchange | A Collection of Biomedical 3D Printable Files and 3D Printing Resources Supported by the National Institutes of Health (NIH)." *NIH.gov*, accessed Oct 8, 2017.

These 3D printed tools are based on the ball and stick molecular modeling kits that started being used in the 1860s.⁶² These kits use spheres that can connect with other individual atoms, where the number of connection sites represent how many sites they have available to bond with other atoms; carbon atoms would have 4 connection sites to represent having 4 open binding sites whereas hydrogen atoms would have 1 hole to show that a hydrogen atom only has one binding site. Along with the spheres, the kits use rods, bars or tubes to connect the atoms together and form molecules. An example of one of the 3D printable modeling kits is shown in Figure 8. Beyond the more standard modeling kits like that in Figure 8, there have also been many variations on the standard stick and balls models. Some versions simplify the models by using 2D profiles that slide together so students can put the molecules together quicker and easier.⁶³ Such an example is shown in row 7 of Table 5. Other kits use different colors for the different *s* and *p* bonds between atoms while modeling.⁶⁴

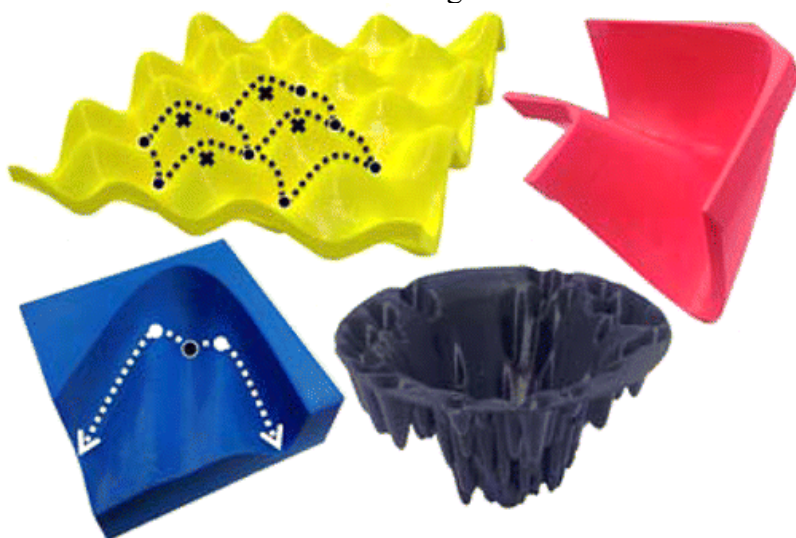


Figure 9. 3D printed free energy topology models. <http://pubs.acs.org> under [CC BY 2.0 by Creative Commons](#)

Chemistry education has just started to utilize the full innovative potential of 3D printing. One example is using it to create 3D topographical representations of the free energy of a reactive chemical system. Examples of some of these surfaces are shown in Figure 9. Using these 3D printed surfaces, it is easy for students to understand why reactions progress along certain paths because they can visually see the troughs and valleys of low energy that the reaction follows to reach the minima. The other benefit is that students can also see why some reactions have multiple stable states, because of multiple free energy minima present.⁶⁵ Another

⁶² "Models and Structural Diagrams in the 1860s." *yale.edu*, accessed Oct 8, 2017.

⁶³ Dean, Natalie L., Corrina Ewan, and J. Scott McIndoe. 2016. "Applying Hand-Held 3D Printing Technology to the Teaching of VSEPR Theory." *Journal of Chemical Education* 93 (9): 1660.

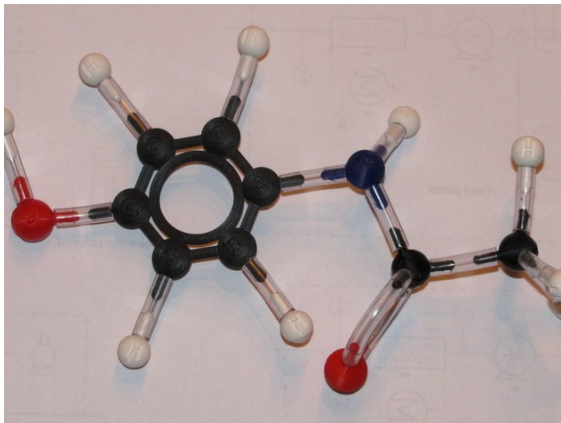
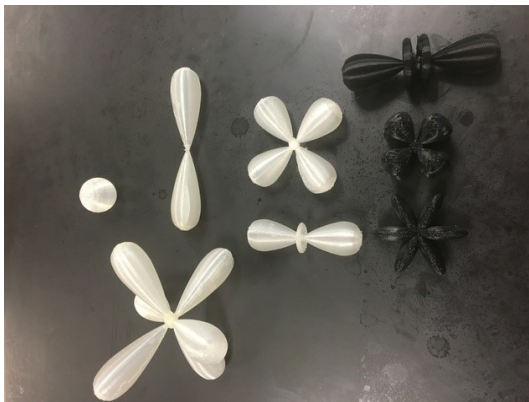

⁶⁴ Smiar, Karen and J. D. Mendez. 2016. "Creating and using Interactive, 3D-Printed Models to Improve Student Comprehension of the Bohr Model of the Atom, Bond Polarity, and Hybridization." *Journal of Chemical Education* 93 (9): 1591.




⁶⁵ Kaliakin, Danil S., Ryan R. Zaari, and Sergey A. Varganov. 2015. "3D Printed Potential and Free Energy Surfaces for Teaching Fundamental Concepts in Physical Chemistry." *Journal of Chemical Education* 92 (12): 2106.

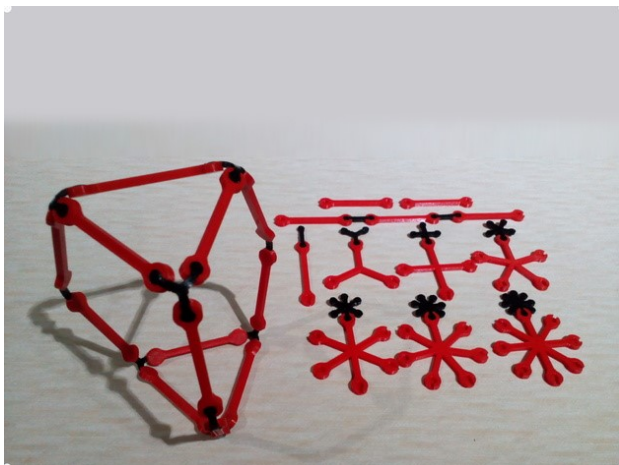
innovative use of 3D printing in chemistry education is to teach students about 3D protein folding in complex structures. Protein folding is perhaps one of the most complex topics due to the sheer number of possible paths and factors during a reaction. At the Scripps Research Institute, researchers developed protein folding models and kits that let students experiment with protein folding using a hands-on approach. Using a hands-on approach, the students are more likely to grasp the concepts involved with protein folding and the influencing factors.⁶⁶ A representative selection of the available tools can be found below in Table 5.

⁶⁶Davenport, Jodi, Silberglitt, Matt and Olson, Arthur. "In Touch with Molecules: Improving Student Learning with Innovative Molecular Models." *Protein Data Bank*, accessed Oct 8, 2017.

Table 5. Example of 3D printed Objects for Chemistry Education

 <p>Acetaminophen molecule made with 3D printed molecular modeling kit. www.thingiverse.com by betawolf under CC BY 2.0 by Creative Commons</p>	<p>3D printable molecular modeling kits are available in many variants. Most are ball and stick modeling kits. Some of the 3D printable kits available have premade subgroups of atoms to simplify construction. These kits allow students to build molecules and perform reactions and see where all the atoms go.</p>
 <p>Atomic Orbital Collection. www.thingiverse.com by chemteacher628 under CC BY 2.0 by Creative Commons</p>	<p>3D printed election orbitals are available to show students the different orbital shapes that elections occupy. These are designed so students can visualize in 3D, the 2D orbital shapes shown in the textbooks that the students use.</p>
 <p>3D Printed DMSE-Tetrapod Molecule. www.thingiverse.com by mechadense under CC BY 2.0 by Creative Commons</p>	<p>3D printed molecule models are available to be printed. Large databases of 3D printable molecules exist with one of the most notable being the National Institute of Health's 3D print exchange. (3dprint.nih.gov) These 3D printed molecules help students visualize molecules that are too complicated to be made easily with molecular modeling kits.</p>

 <p>3D printed free energy topology models. http://pubs.acs.org under CC BY 2.0 by Creative Commons</p>	<p>3D printed surface models of the free energy in reactions. Designed to help students visualize why reactions progress along certain paths and why a reaction may have multiple stable states.</p>
 <p>Protein Modeling Set. www.thingiverse.com by educator under CC BY 2.0 by Creative Commons</p>	<p>3D printed protein modeling and folding sets have been made to help teach organic chemistry. The students are able to arrange and fold the complex protein structures in 3D space to help them visualize what is happening in the complex reactions of proteins.</p>
 <p>3D Printed Centrifuge Adapter. www.thingiverse.com by cathalgarvey under CC BY 2.0 by Creative Commons</p>	<p>3D printed lab equipment for most applications is available. The National Institute of Health's 3D print exchange contains a large database of such equipment. Additional designs for equipment is found at Thingiverse or similar sites. Some of the designs available, but far from the entire collection, include centrifuges, beaker holders, test tube racks, and beaker plugs.</p>

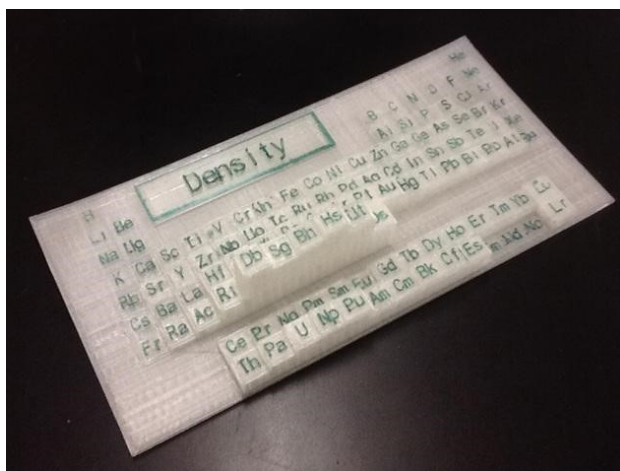


2D

to 3D Flexible Molecular Structures.

www.thingiverse.com by [gyrobot](#) under [CC BY 2.0 by Creative Commons](#)

Flexible 2D to 3D molecular modeling structures have been 3D printed. These models allow the students to make the molecule in 2D on the desk, then bend it to see how that molecule looks in 3D.



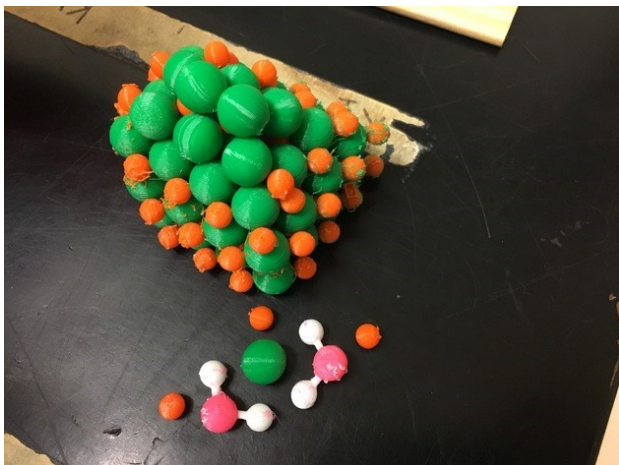
3D Printed Period Density Trend. www.thingiverse.com by [tolle](#) under [CC BY 2.0 by Creative Commons](#)

3D periodic tables have been designed so that students can intuitively visualize periodic trends like atomic density, radii, ionization energy and electronegativity. The idea is that the 3D visualization sticks in students heads better than 2D tables.



3D Printed Alpha Decay Model. www.thingiverse.com by [chemteacher628](#) under [CC BY 2.0 by Creative Commons](#)

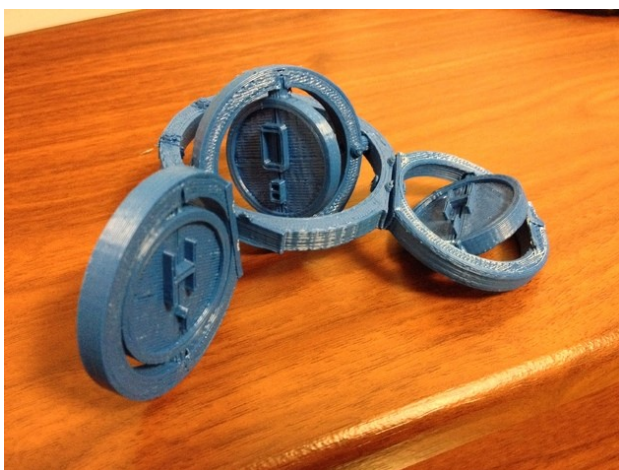
3D printed models of radioactive elements have been made to try to help students visualize what happens during alpha decay. It shows students that the alpha particle is lost from the atom taking protons with it and as such, the element changes.



3D Printed Model of NaCl solubility in water.

www.thingiverse.com by [chemteacher628](#) under [CC BY 2.0 by Creative Commons](#)

Several models have been made that utilize 3D printing to help students visualize how water molecules help dissolve NaCl crystals into ions in the solution



3D Printed H₂O molecule showing electron configuration and bonding. www.thingiverse.com by [chemteacher628](#) under [CC BY 2.0 by Creative Commons](#)

A few versions of molecular models that incorporate visualizations of how electrons are shared and distributed in the molecule exist. These models build on other models of molecules by adding where the electrons would generally reside. A few of the models also incorporate motion to show that the electrons are not static in the molecule and move around.

3. Methodology

This project was intended to improve chemistry education by increasing teachers' access to 3D-printed tools to be used in the classroom, in order to improve students' understanding of challenging concepts in chemistry.

To effectively accomplish the project, we laid out five objectives:

1. Determine the resources available to teachers to 3D print tools for chemistry education.
2. Compile a directory of 3D printed tools and lesson plans chemistry educators can use to address the students' misconceptions and misunderstandings.
3. Create a feasible delivery method of getting 3D-printed tools to chemistry teachers.
4. Develop a simple to use, and comprehensive guide on how to 3D Print simple objects for use in conjunction with other tools.
5. Develop our own 3D printable tools to target specific misconceptions held by students.

The goal of this project was to create a common location where educators could find 3D printed tools that could be implemented in high school chemistry classrooms to help improve their students' learning. We compiled research about common chemistry misconceptions, as well as research about educational techniques that help students learn better. Next, we developed and distributed a survey for chemistry teachers so we could find out firsthand what topics were causing students trouble in chemistry. Concurrently, we began developing ideas for possible 3D printed tools that could be designed and sent to teachers. However, after discovering many designs similar to our own available on the Internet, we began to collect these designs into a compendium, which would exist on a WPI-hosted website, as a resource for chemistry teachers to search and obtain tools to use in their curricula. In addition to the compendium, we also strived to use our researched literature to develop a list of common misconceptions and easy ways to combat them in the classroom by using a combination of our developed physical tools, our compendium, and other online resources. For teachers who are inexperienced with 3D printing and may only want to print a few parts, we created an introductory guide on how to 3D print simple objects.

3.1 Information from Chemistry Teachers

Our research allowed us to catalog a large collection of 3D printing resources from which chemistry teachers can access. These resources include printable part files, a selection of companies that will print and ship a part to you, links to larger databases of printable part files, and a selection of detailed guides on 3D printing. The majority of research on chemistry education dates back to the 1990s. In order to gain more up-to-date knowledge about the current state of chemistry education, we developed a survey for high school teachers to take. WPI requires that students intending to do research with or on people apply for an application with the WPI Institutional Review Board (IRB). The approval from the IRB Office can be found in Appendix D. The survey helped give the perspective of current teachers and their opinions on what their students need in order to succeed in the classroom. The survey contained questions to find which topics students find the most difficult to understand. Knowing these topics allowed the creation of a specially designed tool that could be used to combat the most misunderstood concept. The survey also gauged educators' use and knowledge of 3D printers. This information was used to determine the best method to deliver tools to educators. These methods could include printing the models on a school owned 3D printer, buying a 3D printer, or using a third-party company to create and ship the part.

We decided to use Google Forms to deliver our survey to our target audience.⁶⁷ This allowed any prospective survey takers to easily and quickly fill out and submit the short survey. We decided to send the survey to high school chemistry teachers in the Worcester area. To do so we used three methods: emailing teachers directly, emailing school principals directly, and reaching out through WPI's available resources. The questions sent to these educators were designed to assess which topics students had the most difficulty with and how much access and experience educators have to 3D printers. The questions on student difficulty were asked to judge which topic a 3D printed tool would benefit the most from. The questions on 3D printing were asked to allow us to get an approximation of what the majority of educators have access to, and then be able to create a plan for teachers to gain access to tools.

We also interviewed two current WPI chemistry professors to determine what their views are on the role of 3D printing in chemistry education. The purpose of these interviews was to collect information on which physical models or learning techniques are being used in classrooms. This information further helped to develop a compendium of useful 3D printable tools, as well as an exhaustive list of common misconceptions and ways to combat them. These interviews, as well as our survey, will serve to help us determine what will best suit the needs of chemistry educators.

Professors Brodeur and Heilman taught introductory chemistry classes at WPI. As such, these professors see students who have just recently graduated from high school and also the difficulties and misconceptions that they have not resolved since high school. Our questions for them were similar to the survey we gave to high school chemistry teachers, but slightly more direct and targeted. We specifically asked them which topic students found most difficult to comprehend in order to compare with information we found in our literature research, as seen in the background sections 2.1-2.3. Then, we asked which physical representations are used in their classrooms. Finally, we asked if they thought there were any 3D models that could be created to

⁶⁷ Survey for Chemistry Teachers: <https://goo.gl/forms/M6qL5124JHxiancQ2>

assist in any difficult chemistry topic. This information could potentially be used to help us target a difficult topic and find or create a model that helps explain it.

3.2 Creation of Database of Tools and Lessons

Through our research and development process of creating a useful educational tool, we found that the large majority of our ideas, such as 3D printable molecular modeling kits and periodic trend tables, were already implemented by other people. These tools, however, were scattered across various websites and are hard to locate. We decided to create a database of all of the educational 3D printable tools for chemistry education we found so that educators can quickly search and find what they need instead of searching the internet. This database, hosted on our website, was designed as an access point for educators to find resources that they need. These resources may include 3D printed parts, lesson plans, guides, and more.

To create the database, we manually searched for, and inserted each of the items into an Excel file, complete with name, category, link, description, author, and image. This Excel file was exported as a .csv file (comma-separated value), and then uploaded to the server host. The JavaScript code was written to read, and format this csv file into a readable format which is displayed on the website. The database on our website was created through the use of HTML, Less, CSS, and JavaScript code, which is further detailed in Section 3.3.

Many 3D printed parts in the database came from websites such as Thingiverse, Stratasys, or the National Institutes of Health (NIH) 3D Print Exchange database of molecules. Lesson plans are from Thingiverse Education and Stratasys Education, among others. Guides similarly come from a variety of reliable online sources. Although the focus of our project was on general chemistry education, there were many tools out there that we have included for other subjects such as organic chemistry, biology, and anatomy. We took the liberty of researching the options listed and recommending the resources that we would personally use.

In addition to the database of 3D printed tools from online resources, we compiled a list of web-based resources, such as online simulations, to be used in addition to physical 3D printed tools. To make the best use of these tools, we listed the misconceptions we gathered in our research, as seen in the Background sections 2.1.-2.3 and assigned the tools and simulations that would best aid students in learning the things they have trouble with. This allowed teachers to navigate to the topic or misconception causing difficulty in their classrooms and find the 3D printed tool or online simulation that specifically addresses that trouble area.

We also wrote a guide for those who are new to 3D printing. This guide was meant for people who are new to 3D printing and may only want to use a 3D printer once or twice, and do not want to learn everything about the technology. We also linked to other guides on 3D printing for beginners. These guides could be used by users who do not know what 3D printing is in order to get a complete explanation of what it is, how it works, and the history of it. We have also put in intermediate guides for more experienced users looking for a refresher or a better way to use their printer. This way, any person, whether they own a 3D printer or not, can make use of the database to find what they might need.

3.3 Creation of HTML Compliant Website

In order for educators to find the resources from our database, we developed a website for others to use. Our website was hosted on WPI's servers using current web technologies. The website contains all the information a chemistry educator may need to start printing objects they can use in the classroom. We arranged the website so educators can determine the best method for them to produce 3D printed parts, and then use the database to find what the resources they need to accomplish their goal. The database, as explained in section 3.2, consisted of the resources found during our search. The database was then uploaded to be served to visitors as a .csv file from WPI's servers. The raw Comma Separated Value (CSV) data is dynamically displayed in an easy to view format by a JavaScript rendering task. Anyone with the link to our website could access our website to learn about 3D printing.

Every person has different knowledge of 3D printing. To accommodate various users, we included an interactive, brief survey on the homepage of our website that directs users to specific guides and instructions based on their particular knowledge level. An experienced user will be redirected to advanced instructions on how to print the resources we curated, while an inexperienced user will be directed to a guide with much more details on 3D printing.

There are best practices on making a website. We used the style guide that Google publishes yearly to create a secure and well formatted website.⁶⁸ This style guide advises for good practices and against harmful practices that might be used while writing HTML and CSS code. The guide lists both styling and formatting rules that should be followed when creating a website. The purpose of this guide is so that anyone creating code for a website is following the same style, making it easier to read and edit. Style is comparative to dialect in a language; although two people may speak the same language, they may not be able to understand each other due to differing dialects. Validation of conformity tests were performed to ensure that the code matches the same style as the majority of websites. Table 6 below contains the tools, libraries, and components for different parts of the development process.

⁶⁸ "Google HTML/CSS Style Guide." Google HTML/CSS Style Guide, Google, google.github.io/styleguide/htmlcssguide.html.

Table 6. Tools and Components Used for Our Website Design

Functionality	Tool/Library/Component
HTML, CSS, JS Editor	Netbeans IDE with Web Dev Tools installed
Page Layout Utilities	Bootstrap 4
Page Themes	Bootstrap 4 Compatible Clean Blog Theme
Responsive Elements	JQuery
Widget Support	JQWidgts
CSV Database Parsing	Papa Parse
Minification	JSMIn
FTP Uploading	WinSCP
Other Functionality	Custom

3.4 Design of Physical Tools to Target Specific Misconceptions

In the course of this project, we decided to design tools to target specific chemistry misconceptions for which suitable tools were not available online. We made these tools using SolidWorks Student Edition.⁶⁹ After developing models and converting them to STL files, which are widely recognized by slicers, we sliced them using Cura.⁷⁰ We then exported the sliced GCode files and printed them on a modified Prusa i3 Hictop edition to ensure that the model will print properly. The Prusa i3 is a very base model printer designed for DIYers and people at the entry level of 3D printing.⁷¹ The printer comes in pieces and the customer assembles, codes, and calibrates the printer manually. Although the Prusa i3 Hictop edition is no longer made, newer editions are available for purchase either fully built or in pieces.

Our development process for determining what we should make centered around the difficulties of students as determined from the results of our survey, shown in Section 4.2, and the initial misconceptions found in research, found in Section 2.2. The particular misconceptions and difficulties that we targeted were “Identical molecules can vary in size,” “Breaking bonds releases energy and forming bonds takes energy,” “Energy is required in both the forming and breaking of chemical bonds,” and “There are only 2 types of bonding: ionic and covalent.” We focused on these topics in particular because no available 3D printable tools existed that target these areas. To develop the physical models to address these topics, we brainstormed for several weeks. We looked for inspiration for our brainstorming descriptions and illustrations of these topics in textbooks as well as online visualization tools that try to address the topics. We took the aspects of the sources that we liked and merged them into the 3D models we made.

⁶⁹ SolidWorks Student Edition. <http://www.solidworks.com/sw/industries/education/student-edition.htm>

⁷⁰ Cura. <https://ultimaker.com/en/products/ultimaker-cura-software>

⁷¹ Prusa i3 3D Printer: <https://shop.prusa3d.com/en>

4. Results and Discussion

4.1 Interviews with WPI Chemistry Faculty

In our research, we decided to interview college-level faculty here at WPI to determine concepts they find students struggle with. This should reflect trouble areas of high school students, since difficult topics that were not learned in high school would remain difficult once students reached college-level chemistry. We also wanted to see if WPI faculty had any ideas for tools that could be 3D printed that they would use in their classes to improve students' learning. We interviewed Professor Destin Heilman and Professor Drew Brodeur of the WPI Chemistry Department, and the following sections detail our interviews with each of them. A summary of the interview with Professor Heilman as well as a transcript of the interview with Professor Brodeur can be found in Appendix C.

4.1.1 Interview with Destin Heilman

Destin Heilman is a Chemistry Professor at WPI. He has taught general chemistry and chaired a committee at the school regarding WPI's general chemistry curriculum and how it could be changed. We interviewed him to gain insight into where he has seen students struggle with in his experience teaching. We asked which subjects he finds students struggle with the most, and some he mentioned were:

- Stoichiometry
- Mole Theory
- Molecular Geometry
- Acid-Base Equilibrium

The difficult areas that Professor Heilman mentioned in the interview match well with the expected difficulty areas. Stoichiometry, Molecular Geometry, and Acid-Base Equilibrium were all misconceptions we found in our background research (Section 2.2) and in our survey results (Section 4.2). Mole Theory was a topic that we had not encountered in our background research but was encountered in our survey results (Section 4.2). Based on the similarities between Professor Heilman's experience of misunderstood topics and the correlation to our research and survey results, we concluded that we were on the right track.

Next, we asked about educational tools he already uses, which are listed below:

- Physical Tools
 - Standard Molecular Modeling Kits
 - Ball-and-stick molecular modeling kits are standard in chemistry classes for viewing basic molecules
 - Scaffolding Tool for Crystal Lattice Structures
 - This tool allows students to see the bonding between individual atoms in a crystal lattice by stacking them in a scaffold structure
 - 3D Projection System at WPI for 3D molecular geometry

- Teachers can project molecules that can be seen as 3D using green-magenta 3D glasses
 - Software Tools
 - MolView for seeing molecules in 3D space⁷²
 - MolView is an online app used to build and rotate molecules in 3D space.
 - ALEKS Software⁷³
 - “ALEKS is an adaptive, artificially-intelligent learning system that provides students with an individualized learning experience tailored to their unique strengths and weaknesses.”⁷⁴

Then, Professor Heilman talked about educational changes he had tried implementing at WPI in chemistry labs, and ways to improve chemistry lectures, such as:

- Lab demos in lectures using mobile chemical hoods
- Project-based labs which grade based on engagement instead of results

Lastly, we discussed how 3D Printing could be used to develop new tools for use in the classroom to help students. We explained to him an idea of ours to use Velcro on molecular models to show intermolecular forces, and he expanded the idea to use weak magnets to show intermolecular forces, and to use stronger magnets to show molecular bonds that are much stronger than secondary bonds. This could also show the movement of hydrogen between different water molecules, and the constant exchange of hydrogen between hydroxide and hydronium, which leads to acidity or alkalinity in a solution. Professor Heilman said proton transfer is another area where a physical representation would help students understand the topic better. See Appendix C for an extended summary of this interview.

4.1.2 Interview with Drew Brodeur

Drew Brodeur is a Chemistry Professor at WPI. He has taught each course in the general chemistry sequence. We interviewed him to gain insight into which topics he has seen students struggle with. We first asked what topics he found students had trouble with, and Professor Brodeur described issues in each class of WPI’s chemistry sequence, as outlined below.

- Difficult Areas
 - Chemistry 1010
 - Atomic Structure
 - Electronic Structure
 - Excitation of Electrons
 - Geometry of Hybrid Orbitals
 - Chemistry 1020
 - Stoichiometry
 - Chemical Reactions

⁷² <http://molview.org/>

⁷³ <https://www.aleks.com/>

⁷⁴ <https://www.aleks.com/highered>

- Thermochemistry
- Chemistry 1030
 - Acid-Base Chemistry
 - Buffer Chemistry
 - Equilibrium
 - Reversibility of Reactions
- Chemistry 1040
 - Electrochemistry
 - Polymer Chemistry
 - Spectroscopy

The difficult areas that Professor Brodeur mentioned in the interview matched well with the expected difficulty areas. Atomic Structure, Acid-Base Chemistry, Equilibrium and Reaction Rate Chemistry, and Thermochemistry were all misconceptions we found in our background research (Section 2.2) and in our survey results (Section 4.2). Hybrid Orbital Geometry was a topic that we had not encountered in our background research but was encountered in our survey results (Section 4.2). Based on the similarities between Professor Brodeur's experience of misunderstood topics and the correlation to our research and survey results, we concluded that we were on the right track.

He also suggested ways 3D printing could help in teaching chemistry, as seen below:

- Higher Quantum Number Orbitals
 - E.g. 4f, 3p, or 4p
- Electron Distribution
 - Partial positive and negative charge
- Higher Level Chemistry Topics
 - Protein Binding
 - Inorganic Symmetry Groups

The topics listed above are areas where Professor Brodeur found that 3D visualization factors could significantly improve the quality of education in the chemistry classroom. For visualizing higher order quantum orbitals, we found one model on Thingiverse, "Atomic Orbital Collection".⁷⁵ That model, shown below in Figure 10, shows the shape of various orbital shapes including the ones mentioned above. There are also some models on proteins, which could be used to demonstrate protein binding. For Electron distribution and inorganic symmetry groups, there were no models online that we found which could help with these topics. For a transcript of this interview see Appendix C.

⁷⁵Atomic Orbital Collection, *Thingiverse*. <https://www.thingiverse.com/thing:1194700>

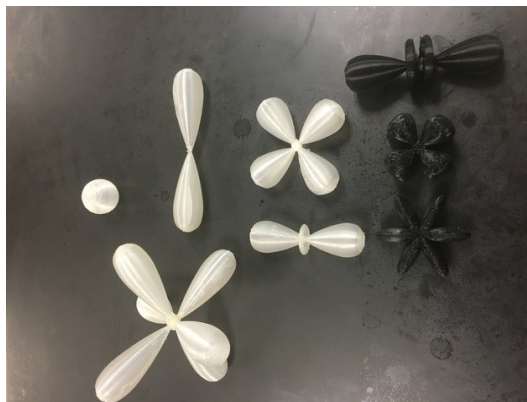


Figure 10. Atomic orbital printed collection. www.thingiverse.com by [chemteacher628](#) under [CC BY 2.0](#) by Creative Commons

4.2 Survey of Local High School Chemistry Teachers

We also sought to better understand which topics chemistry students found most difficult. We designed a survey, found in Appendix E, with IRB approval listed in Appendix D, and distributed it to chemistry teachers in the Worcester area. We received 11 responses, the results of which are detailed in the following text.

One question asked teachers to select topics students found most difficult, so that we could tailor our project to address those certain topics. A graph showing topics teachers selected is shown in Figure 11 below. Other topics suggested by the teachers included mole concepts, stoichiometry, and hybrid orbitals.

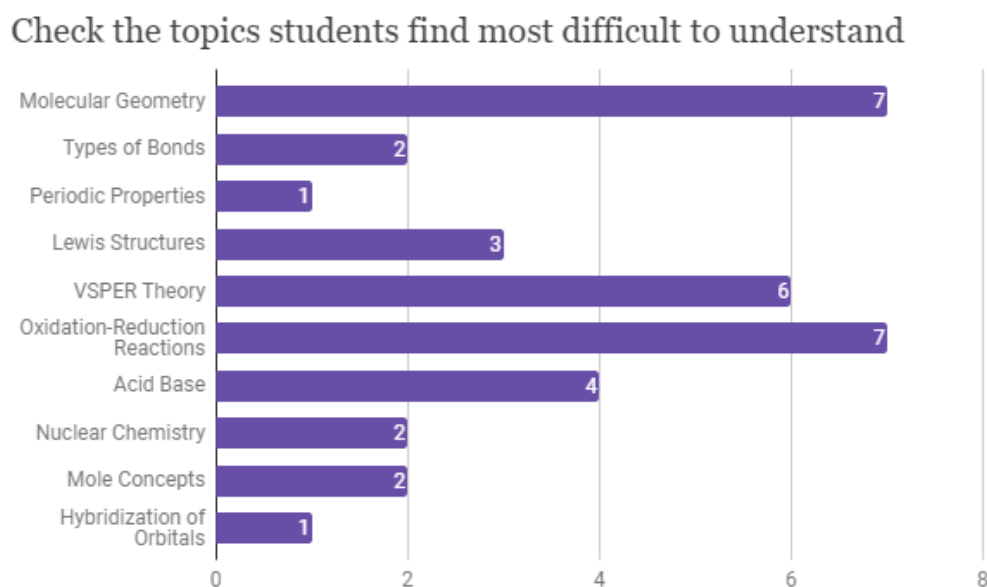


Figure 11. Graph of survey results showing topics students struggle with, according to high school chemistry teachers.

As seen in Figure 11, the most common areas of difficulty as suggested by teachers are “Molecular Geometry” and “Reduction-Oxidation” (redox) reactions, for which 7 out of 11 teachers agreed were difficult for students. The next highest was VSEPR Theory, for which 6 out of 11 teachers agreed was a difficult topic. This data could suggest areas where a physical representation could benefit the classroom most. However, molecular geometry is the area where a majority of 3D representations already exist. This information guided us in the creation of our tools that we designed in Section 4.7. Based on the results in Figure 11, our focus was placed on the topics of Molecular Geometry, Lewis Structures, and VSEPR theory.

Next, we asked teachers what tools they already use in their classrooms, the results of which are shown in Figure 12. We also asked them if they had ideas for topics or tools that would be helpful in their classes, shown in Figure 13. From these results in Figure 12, we can see that many teachers already use molecular modeling kits in classrooms, as well as some that use other household items as tools to show chemistry concepts. In Figure 13, we can see that teachers have many different ideas for possible tools and subjects, including intermolecular forces, lone pairs of electrons, and hybridized orbitals, among other topics. From this, we can see that although there are many tools available on sites like Thingiverse, which have already been

created, teachers either did not know about these, or did not have access to 3D printers and therefore cannot utilize these tools. This was something important that we hoped to fix, by bringing the tools and guides on 3D printing into one place, so teachers can easily find what they need, and use printed objects in their classroom.

What physical objects or representations (Molecule Modeling Kit, Orbital Models, etc.) do you use in your classroom?

10 responses

Molecular models.
Molecule modeling Kit, Snatoms kit
We build "Bucky balls", other than that there is no hands on, physical objects or representations.
Both Molecular Modeling and orbital Models
ball and stick model kits, atomic orbital model,
Modeling kits, other models of geometric shapes and crystal structures.
molecular modeling kits, orbital models, styrofoam models of bonds
molecule modeling kit
molecular models, water molecule models to show intermolecular forces in liquid and solids, ionic crystal models,
Molecular modeling kits

Figure 12. Summary of educational tools teachers already use in their classes to help students.

What types of 3D printed objects do you think would be useful for teaching chemistry?

9 responses

Molecules that could connect together to show intermolecular forces.
I'm not sure
Anything hands on. Models of atoms, molecular geometry, types of bonds, states of matter, intramolecular forces, gas laws, just to name a few. Models that can go along with a real life example or event would be helpful.
I use beans, corn, beads , balloons, covering topics such as , Isotopes, Radioactivity, Bonding, & Electron probability
atomic model kits, I am not familiar with 3D printers so I am not sure what else is possible.
Models to show the hybridized orbitals in relation to each other in a bond
molecule that shows lone pairs of electrons, pi bonding; Bohr model with movable electrons to show electron transitions
acid ionization models for strong and weak acids, models for creating ionic compounds with a net zero charge, models to illustrate the P, V, T and n relationships for gases.
A representation of a small atom (Ex. Fluorine) showing the shapes of the orbitals and their relative sizes

Figure 13. Summary of possible 3D printed objects or ideas which teachers indicated might help in classrooms.

Another important aspect of our project was whether or not most teachers have access to 3D printers or knowledge about 3D printing in general. First, we asked teachers if they had access to a 3D printer, the results of which shown in Figure 14 below. We also asked if they had ever used a 3D printer before, the results of which are shown in Figure 15. Additionally, we asked if they had ever heard of, used, or were unfamiliar with certain 3D printing resources, such as Shapeways, Thingiverse, 3D Hubs, etc. Those results are shown in Figure 16. Based on the results shown, the teachers that completed our survey have not used a 3D printer before or have not heard of any 3D printing resources, but some might have access to a printer at their school. For this reason, creating 3D printing guides and compiling 3D printed resources together in one easy location would provide one possible solution. Since the teachers don't know what resources exist or where to find them and they don't know how to use a 3D printer, we could reduce the entry level barrier for 3D printing by providing all the information in one place.

Do you have access to 3D printers where you teach?

11 responses

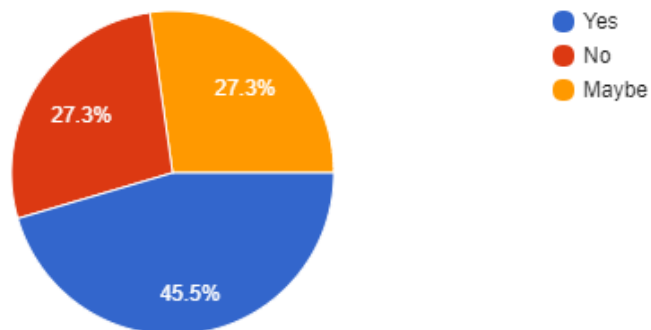


Figure 14. Pie chart showing teachers' access to 3D printers.

Have you used a 3D printer before?

11 responses

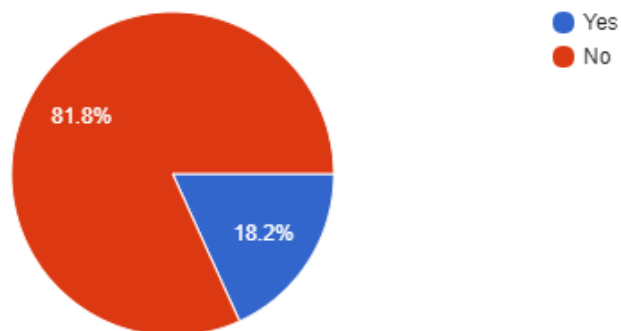


Figure 15. Pie chart showing teacher's experience using 3D printers.

How familiar are you with these 3D printing resources?

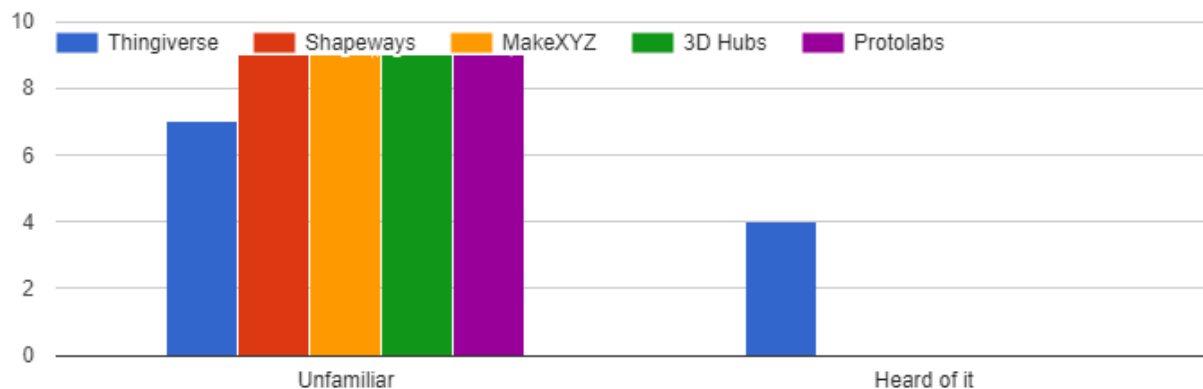


Figure 16. Chart showing teachers' familiarity with certain 3D Printing resources.

We also asked teachers how much time or money they would be willing to invest in making or purchasing a 3D printed tool to use in class. Some of their responses are shown in Figures 17 and 18. We found that teachers in general have very little knowledge about 3D printers, despite having a reasonable amount of access. As we can see from Figure 14, about 46% of teachers had access to 3D printers, while 27% did not have access, and another 27% are unsure. From Figure 15, however, we can see that only 18% of teachers had used a 3D printer before, while 82% had not. From these results, we could conclude that many teachers might have access to 3D printers and the main obstacle becomes learning how to use them, in order to make tools that can be used in the classroom.

How much time would you be willing to put into printing out and assembling a 3D printed teaching aid?

10 responses

3 hours
2-3 hours
An hour?
I don't have any time. But I would be willing to recruit some seniors to help me out with it. It could be a good experience for them.
10-20 minutes
1 hour
If it works, as much time as it needs.
If it's a permanent tool, plenty
Whatever time it takes
All of the time required - it would be time well spent.

Figure 17. A summary of teachers' willingness to invest time into a 3D printed tool.

What would you be willing to pay for a 3D printed teaching aid (such as costs to print)?

8 responses

Yes..
Depends on the cost and how useful the materials are
Depends...small items \$8-10, medium \$25-35. I don't know if the school budget will cover it. Those prices are what I would pay out of pocket.
I don't know. I will use it ONLY if cost is affordable and reasonable
Out of pocket, \$25.
Yes.
I think I'd need to see the product to gauge its value
Yes

Figure 18. A summary of teachers' willingness to invest money into a 3D printed tool.

The results also show that the most any teacher would be willing to pay for a 3D printed tool would be around \$35, and the maximum amount of time any teacher would be willing to invest would be about 3 hours. These results suggest that most teachers do not want to spend more than 1-2 hours on printing a part and the most a teacher indicated they would pay was \$35.

This low time investment makes it difficult to design a guide that will let the teachers print a part, since they don't have the time to really learn or understand how to use a 3D printer. For people with 3D printing experience, printing a part takes about an hour of effort and ~\$2-\$8. Our survey, however, showed that many teachers don't know how to use a printer, and the time required would be 4+ hours for many since they would have to learn how to use the printer as they go. The option to address the time constraints or inexperience with 3D printing is to use a 3D printing service. The low-cost teachers are willing to pay, however, means that 3D printing services are not typically a feasible option either (see Section 4.4). While such services are easier to use, they cost much more to use, with even small 1-2" parts cost \$20+, and many parts costing \$40+, as detailed in section 4.4. Another option for the teachers is to find someone who has 3D printing experience or a 3D printer and use this person as help.

4.3 Cost Analysis of 3D Printed Molecular Modeling Kit

High cost may prohibit teachers from using 3D printers. We accordingly performed some economic analysis to determine potential costs of 3D printed tools. Since molecular modeling kits are a very common item used in chemistry classrooms, and possibly the best way to address issues with students' understanding of VSEPR, Lewis Structures and Molecular Shapes, we decided to investigate if it would be feasible to 3D print a molecular modeling kit. We performed a cost analysis comparing an average molecular modeling kit that can be found on Amazon to a hypothetical 3D printed kit to determine the practicality of 3D printing a molecular modeling kit. Ideally the 3D printed molecular modeling kit would need to be of equal or less cost than the commercially available kit. For the purpose of comparing raw costs, the only factor we considered contributing to the cost of the 3D printed model was the cost of the raw plastic filament material needed to make the model, and we ignored labor costs.

4.3.1 Baseline Molecular Modeling Kit on Amazon

The modeling kit that was decided as the baseline was a 239-piece kit made by Atomic Architect consisting of 86 atoms and 153 bonds.⁷⁶ The kit as sold on Amazon was a price of \$24.00 at the time of our calculations. The large atoms in the kit are around 1.125" in diameter and the bonds are around 1" in length on average. The average cost per piece of the kit comes to \$0.1004 delivered, which includes markup, shipping and other costs. The cost can be found in row 1 of Table 7.

⁷⁶ "Molecular Model Kit Biochemistry (240 Pieces) - Chemistry Organic and Inorganic Modeling Students Set." *Amazon*, accessed Oct 28, 2017.

Table 7. Comparison of modeling kit prices.

Kit	Price	Size Factor	Time Per 10 Kits
Amazon Kit	\$24.00	100%	~10 Minutes
Equivalent 3D Printed Kit	\$41.05	100%	80 Machine Hours 20 Person Hours
Competitive 3D Printed Kit	\$23.47	77.5% (Average)	70 Machine Hours 20 Person Hours

4.3.2 Hypothetical 3D Printed Kit Equivalent to Amazon Baseline

For an equivalent 3D printed kit, the resulting cost per kit was almost double the cost of buying the kit on Amazon. To be considered equivalent, the size, volume and quantity of plastic for the 3D printed kit had to match that of the Amazon kit. To calculate the cost of the 3D printed kit we calculated the volume of the parts, accounting for infill percentages (amount of plastic in the part) and multiplied the volume by the cost per cubic inch of ABS filament.⁷⁷ Appendix G summarizes our calculations. For the atoms, the volume came out to 0.62 cubic inches, a little less than that of a full 1.125” sphere because of the holes for bonds. The bonds were close enough to cylinders to be considered cylinders, and their volume came out to 0.07 cubic inches. Given the 86 atoms and 153 bonds per kit, the total volume is 64.03 cubic-inches of plastic. Once the added volume of support material needed to support the objects is added in, the volume comes to 87.34 cubic inches. The cost of ABS plastic is \$0.47 per cubic inch as listed on Amazon. Given this information, the cost of a single 3D printed modeling kit was \$41.05, compared to \$24 directly from Amazon as shown in Table 6. The average cost per piece of the kit came to \$0.1717 which is almost double the cost of the kit found on Amazon.

In addition to the cost of the 3D printed kit, the time to produce a kit on an FDM printer was calculated. The average print speed of the printer was assumed to be 70mm/s which is about as fast as a decent object can be printed. Based on this print speed, a single kit would take 8 hours of machine time to print one kit. Given that only about 20 objects comfortably fit on a 6”x6” build plate, it would take 12 prints to make a single kit. If it only took 10 minutes to remove the parts from a plate, prep the plate for the next print, and clean support material off the printed parts, then each kit would take 2 person-hours to make. While the time might be reasonable for printing a single kit, once multiple kits are produced, the time factor also becomes impractical. When 10 kits are produced, it would take 80 printing hours and 20-person hours to make the 10 kits. This is highly impractical when 10 kits can be ordered in minutes, at a cheaper price, online.

At the time of this paper, 3D printing an equivalent kit to those found on Amazon is completely impractical. The 3D printed kits cost much more and require a lot of invested time compared to purchasing the kits online. We figured that although an equivalent kit was impossible to achieve, there might be a kit size (e.g. using less plastic) where a 3D printed kit might be a reasonable alternative. In the following section, we find the necessary size such a kit would need to be to be cost effective.

⁷⁷ See Appendix G for calculations.

4.3.3 Cost Effective 3D Printed Molecular Modeling Kit

Since an equivalent 3D printed molecular modeling kit is currently not cost competitive with commercial kits, we determined the point (i.e. size) at which printing such a kit would become practical. Since the cost of filament is the bottleneck in 3D printed costs, the only way to reduce cost is to reduce the part volumes, which would reduce the amount of filament. We looked at reducing the size of the molecular kits to determine when the 3D printed cost would be competitive with Amazon's prices. We did impose practical constraints, before applying our scaling. The first constraint was that the printed bonds could not shrink their diameter below 1/5" for the sake of rigidity and durability once produced. The other constraint was that the largest dimension of any part should not fall below 1/2" to ensure easy printability.

Because volume varies with the third power of size ($V \propto x^3$), for every doubling of size, the volume increases by a factor of 8 ($2^3 = 8$). Conversely, to decrease the volume by 50%, the size must shrink by a factor of 12.5% ($0.5^3 = 0.125$). Given our constraints, however, we were not able to directly shrink all the parts by a factor of 12.5%. The bonds between atoms would have become too small, 1/8" in diameter, which violated one of our constraints. That extra volume that remained from the bonds, were removed from the atoms. The overall size reduction of the bonds ended up being 11% and the reduction of the atoms was 22% with 40% infill on the atoms. Calculations for size reductions can be found in Appendix G. This reduced the overall volume enough to the point that the model was equal in cost per piece to the Amazon modeling kit as shown in Table 6. The size of the modeling kit once scaled, however, was around 0.75" diameter for the atoms, compared to 1.125" in the Amazon kit. At this size, the modeling kit is quite small. While this might be fine for some applications, from our experience, the reduced durability of parts at the smaller scale would render the modeling kit not be durable enough for its intended use. The time requirements for printing 10 kits at the reduced size was still 70 hours of machine time and 20 people-hours, whereas a similar kit on Amazon can be purchased with little effort and cost.

4.4 Cost Analysis of Different 3D Printing Services

For those who do not own a 3D printer, 3D printing services are available online. These services allow a part file to be submitted online and the company prints the part on their printer and ships it to the customer. We obtained quotes from eight common printing services to determine which ones were cheapest, and to determine the viability of using such printing services. The prices we were quoted for each part from each service are shown below in Tables 8 and 9. The results are sorted in ascending order of price. A comparison point for printing on a self-owned printer is shown at the top of each table (as calculated based on amount of filament used).

The cost of these services is heavily based on their demand at the time of printing, so their costs will vary greatly based on time. Printer type availability isn't the only factor; part size, part complexity, print time, print material, and desired print quality all impact which printers a service has that can fulfill the order request and thus alters the pricing. While many services do a good job predicting their availability to keep costs consistent (Shapeways, Stratasys Direct, 3D Systems)⁷⁸, other services do not, which can lead to varying prices. Lower cost services typically come with a lower quality part⁷⁹. Based on industry knowledge, many lower cost services achieve their low costs by running printers fast, which means less resolution, so they can produce more parts per hour which in turn reduces the overhead costs and the final part cost.

From the list of companies below, we have personally used 3DHubs, Shapeways, and Stratasys Direct to print objects before we started the current Interactive Qualifying Project. The 3DHubs part was cheaper than the others but lacked a smooth surface finish. The layers were clearly visible, and tight ($<0.005''$), dimensionally accurate, tolerances, which means the final printed part was within $0.005''$ of the submitted 3D part file. The Shapeways parts and the Stratasys Direct parts were high quality and came out with tight ($<0.005''$), dimensionally accurate, tolerances and very nice surface finishes with barely visible lines between layers. Based on our experiences, for high quality parts we recommend the more expensive 3D printer services, like Shapeways or Stratasys Direct. For parts that do not need to print to the exact specifications of the 3D part file, or do not need to look as nice, 3DHubs would be sufficient.

The quotations we received during our research matched our personal experiences with the services we mentioned above. The cheapest online service to buy a part from was 3DHubs. It was consistently the cheapest option for each part we received a quotation for as seen in tables 8 and 9. 3DHubs is a slightly different service than the others. Instead of owning 3D printers themselves, 3DHubs acts as a middleman between a buyer and a local person printing the part. The buyer has no knowledge of who is printing the part, or what the final quality of the part will be. 3DHubs takes the part file and calculates a price for which the part could be printed based on the available people in the area with 3D printers capable of printing your part. This service is good for getting a quick part made, but there is no guarantee of the quality of the part received, as this is often a side business people run to make a little money off their printer. That said, the majority of parts printed through 3DHubs would be acceptable for classroom use based on our personal previous use of the service mentioned earlier. The next overall cheapest option was SD3D, a professional 3D printing service in California. It was the second cheapest option for the

⁷⁸“How 3D prints are priced”, *Shapeways*. Accessed 12/4/17. <https://www.shapeways.com/support/pricing/>

⁷⁹ See section 2.4.1 How 3D Printers Work, for more information on quality

part in Table 8 and the 5th cheapest in Table 9. While being only the 5th cheapest, it was still a comparable price to the 2nd-4th cheapest options.

3D printing company prices can vary day to day because of printer availability, part size, part complexity, print time, print material, and desired print quality. It is therefore recommended to get a quote from each printing service on the day that you wish to purchase the part since the cost can vary greatly. Waiting for the price to drop by re-submitting a part may not help as the price may not fall. Additionally, repeatedly submitting the same part for a quotation is in general frowned upon as it shows a distrust of the service quoting the part. For example, identical prints were quoted at \$26.42 on 3DHubs on 11/30/17 and \$19.00 on 12/4/17. Therefore, we recommend investigating multiple services at the time of printing to determine which is the best for the part being printed. We have also included information on the cost to run a self-owned 3D printer as a comparison. These costs are significantly lower and are solely based on the cost of buying plastic filament. For users planning on printing many items in the long run, it would be best to purchase a 3D printer rather than using a commercial 3D printing service. However, for users looking to print a single part, it may be reasonable to use an online service.

Table 8. Cost of representative 3D Printing services to print a “Periodic Trend Density Part” (<https://www.thingiverse.com/thing:52778>). The cheapest printing option was selected from each company. Quotes from 11/30/17.

Method	Cost (Dollars)
Material on Self Owned Printer	\$4.74 (35 hours)
3DHubs	\$26.42
SD3D*	\$67.31
Stratasys Direct*	\$117.07
Protolabs**	\$145.00
3D Printing Studios*	\$150.00
Shapeways	\$151.27
3D Systems**	\$155.11
Materialise OnSite	\$212.16

*-Industrial Supplier, still accessible to individuals, but not friendly to use.

** -Industrial Supplier, not designed for personal use.

Table 9. Cost of representative 3D printing services to print “Ethanol Molecule Part” (<https://www.thingiverse.com/thing:873877>). The cheapest printing option was selected from each company. Quotes are from 11/30/17.

Method	Cost (Dollars)
Material on Self Owned Printer	\$3.06 (28 hours)
3DHubs	\$9.48
Shapeways	\$13.49
Materialise OnSite	\$21.34
3D Systems**	\$25.00
SD3D*	\$35.11
3d Printing Studios*	\$48.69
Stratasys Direct*	\$49.06
Protolabs**	\$57.00

*-Industrial Supplier, still accessible to individuals, but not friendly to use.

**-Industrial Supplier, not designed for personal use.

We recommend Shapeways to customers whom are looking for a good quality, dimensionally accurate part with a good surface finish that will come out exactly the way the user orders it. A high-quality part is one that prints very close to the file specifications and is smooth and dimensionally accurate. 3DHubs is also a good resource for low cost parts, but the quality can range greatly. A part that you order from this service could be the cheapest option but there could likely be visual defects. These recommendations are based off of our extensive personal use of the Shapeways, 3DHubs, and Stratasys Direct services, which we describe above.

4.5 Website and Compendium Development

Our final website created hosted at the link <https://users.wpi.edu/~chem3dprint>. A map of our website is found in Figure 19. Our final website homepage is shown in Figure 20. Before we started this project, we hypothesized that there were not that many 3D printed tools being used in education since few tools were available. However, in the course of our research, we found that there are many such tools in existence, but that they are not very well-known or organized. Therefore, one of the primary deliverables of our IQP was a comprehensive website to bring together assets chemistry teachers might need to begin 3D printing tools to aid them in teaching chemistry. These tools were previously tedious to find since they were spread out across many different websites and not organized effectively in one place. To accomplish our goal of making these resources accessible to chemistry teachers, we created three main areas on the website: a compendium of resources, a list of common student struggles, and a 3D printing guide. Figure 19 shows a map of these areas on our website. These three areas are found under the links to “Resources”, “Chemistry Misconceptions”, and “3D Printing Guide”, respectively. The compendium on the Resources page contained information on 3D printable tools, and lesson plans to learn how to 3D print an object. The list of common student struggles found on the “Chemistry Misconceptions” page contained a list of misconceptions we found in our research, as seen in Section 2.2, along with ideas to address them. Finally, a short 3D printing guide on the “3D Printing Guide” page was created to help teachers learn to print parts in a simple way. Other guides exist but are often complex or too technical. Our homepage had a short “start-here guide” on how to effectively use our website on the home page shown in Figure 20. The guide contained a three-question survey which judges the users’ 3D printing experience and advises them on their best course of action. Additional website images beyond those in this section can be found in Appendix H.

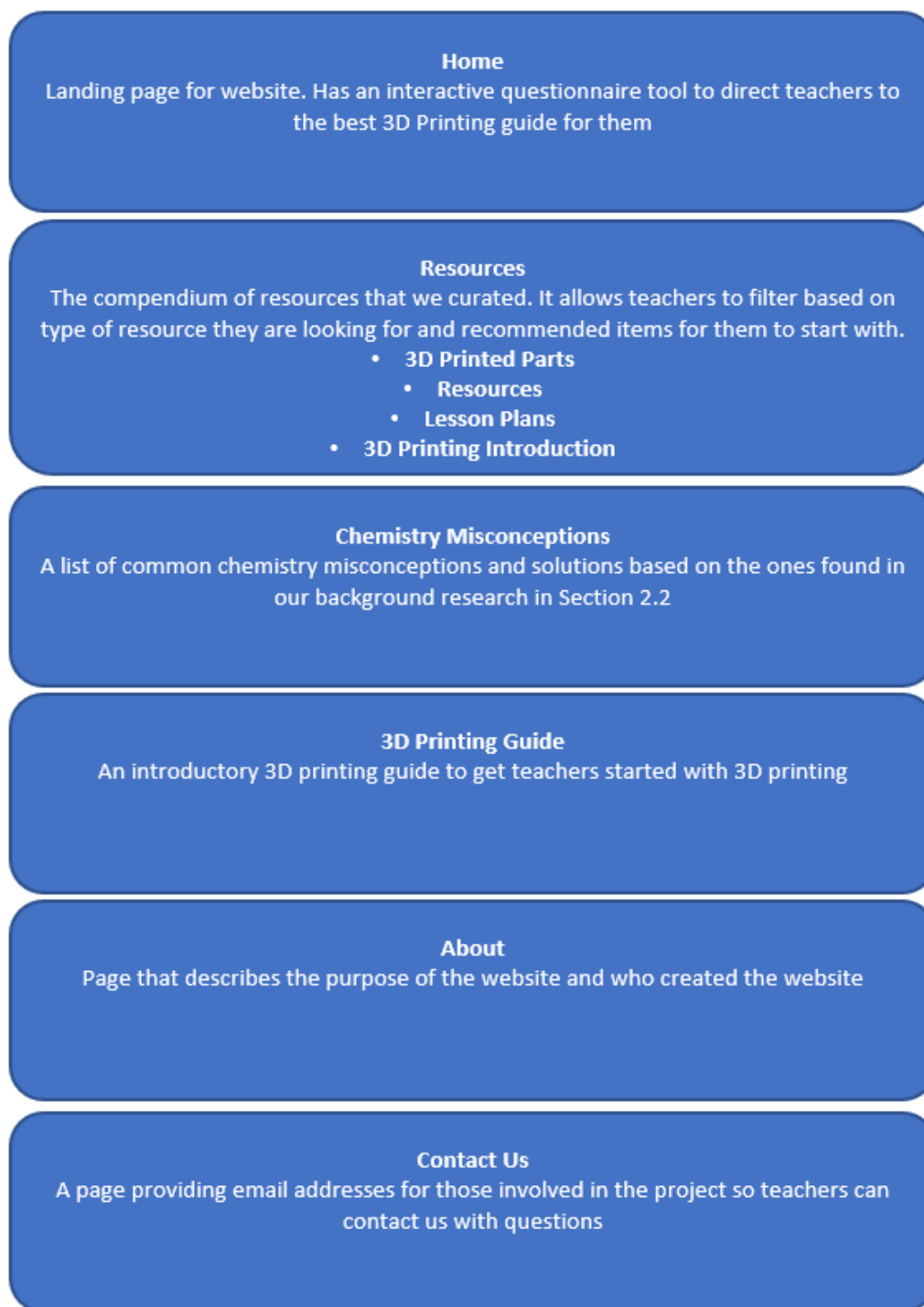
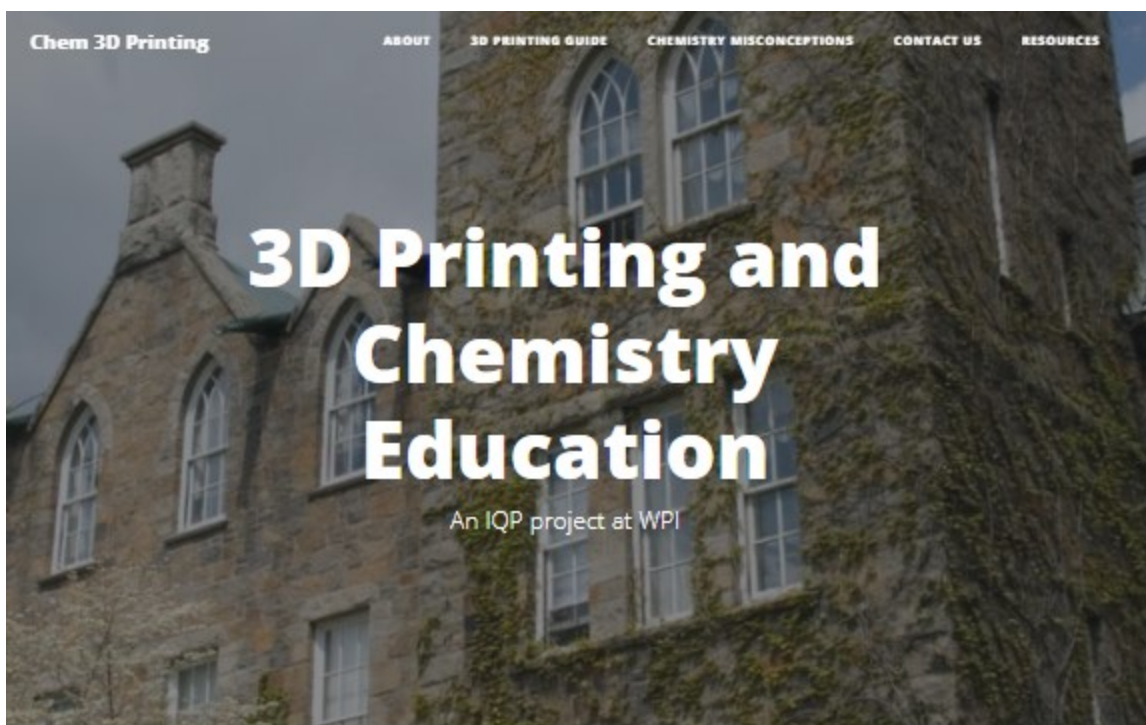


Figure 19. Sitemap of our website.



Start Here

Chemistry education can be tough without sufficient resources or models to complement teaching. That's why we are here to help you. With the use of 3D printing and our compendium of resources, you can find anything from lesson plans to 3D printable object files. You can dive right into the [Compendium of Resources](#) or you can answer a few questions below to get a [personalized guide](#).

On the navigation bar, you can find out a little more [About](#) us and the project we are working on. Have a 3D printer and don't know how to use it? Visit our simple [3D Printing Guide](#). You can also the [Search Resources](#) button to find chemistry related 3D printable objects and resources for the classroom, or personal use. We also have a list of [Chemistry Misconceptions](#) that includes ways to resolve common chemistry struggles. Have some feedback or questions? Don't be afraid to [Contact Us](#)!

Personalized Guide:


Do you know what 3D printing is?

Figure 20. Home page of website. A Personalized Guide widget is shown at the bottom.

On the homepage of the website we created a “Personalized Guide” widget, shown in the bottom of Figure 20, that asks teachers three questions and then directs them to appropriate resources to start with based on their current knowledge level. The three questions the widget

asks are “Do you know what 3D printing is?”, “Do you have access to a 3D printer?”, and “Do you know how to use a 3D printer?” These three questions were chosen because they were able to determine the knowledge and resources the visitor had. The first group of people had very little knowledge of 3D printing. These people were given the most basic 3D printing information to get started with printing. The second group of people knew what 3D printing is but didn’t have access to a 3D printer. These people were given guides that direct them on how to use the commercial 3D printing services available which don’t require owning a 3D printer. The third group of people had a 3D printer and knowledge of what 3D printing is but didn’t know how to use the printer. These people were directed to our 3D printing guide and other 3D printing guides so they could successfully print on their printer. The last group of people knew about 3D printing, had access to a 3D printer, and knew how to use it. These people were directed to advanced 3D printing guides to refresh their knowledge and learn new 3D printing tips and tricks. A flow chart of our “Personalized Guide” is shown in Figure 21. Our “Personalized Guide” helped direct visitors to information on 3D printing appropriate to the visitor’s level.

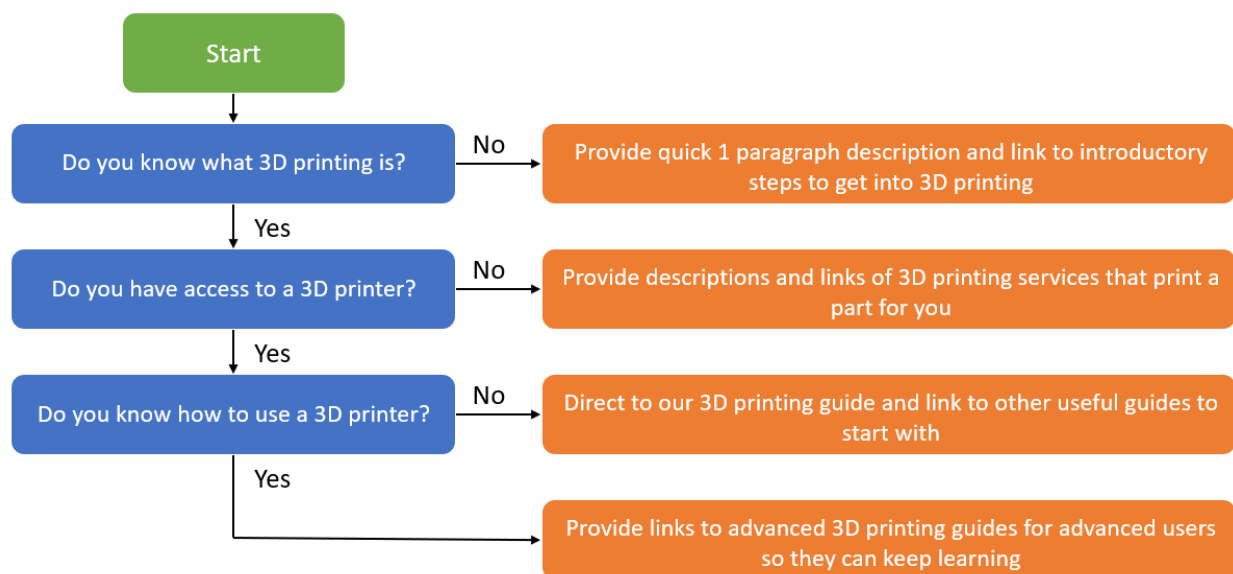


Figure 21. Flowchart of the “Personalized Guide”

The primary feature of this website was a compendium on the “Resources” page containing 3D printable chemistry education tools from various sources on the internet that teachers could use to help explain difficult concepts, shown in Figures 22-25. We set out to collect a compendium of 3D printable tools that could be easily printed and implemented in classrooms. After collecting information on many of these tools from online sources, such as Thingiverse and the NIH 3D Print Exchange, we organized them on our website into four categories (which are shown in Figure 22): “3D Printed Parts”, “Resources”, “Lesson Plans”, and “3D Printing Introduction.” These categories represented the available chemistry tools, generic resources related to 3D printing (part databases, 3D printing services, and databases of 3D printers on the market), lesson plans to incorporate 3D printing into the classroom, and materials to get started with 3D printing. We chose these categories so that teachers could easily select the type of information they are interested in. “3D Printed Parts”, seen in Figure 22, contains a large number of files from part databases like Thingiverse which can be printed and used to teach difficult chemistry concepts or for practical applications such as in a lab. “Resources,” seen in

Figure 23, contains a list of other websites that can be used to find 3D printable parts, databases of 3D printers on the market, as some of the 3D printing services from which to order parts printed to desired specifications. “Lesson Plans,” seen in Figure 24, contains a list of lessons that educators can follow to teach students how to use a 3D printer. These lesson plans come from sources such as Thingiverse Education and Stratasys Education. Lastly, “3D Printing Introduction,” seen in Figure 25, is a list of guides from other websites on how to 3D print an object. These guides differ from the one on our website in their length and complexity. These guides go over anything from the history of 3D printing to how to calibrate your 3D printer.

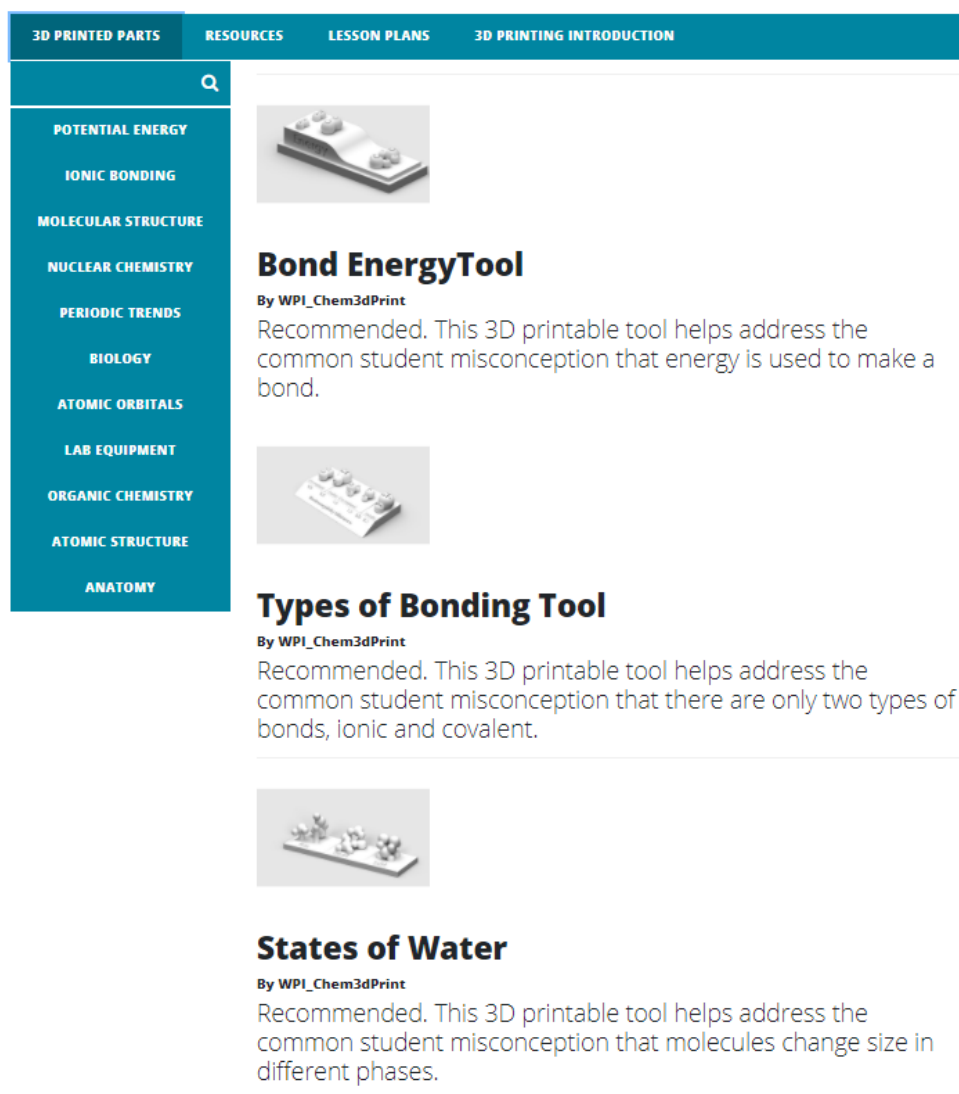
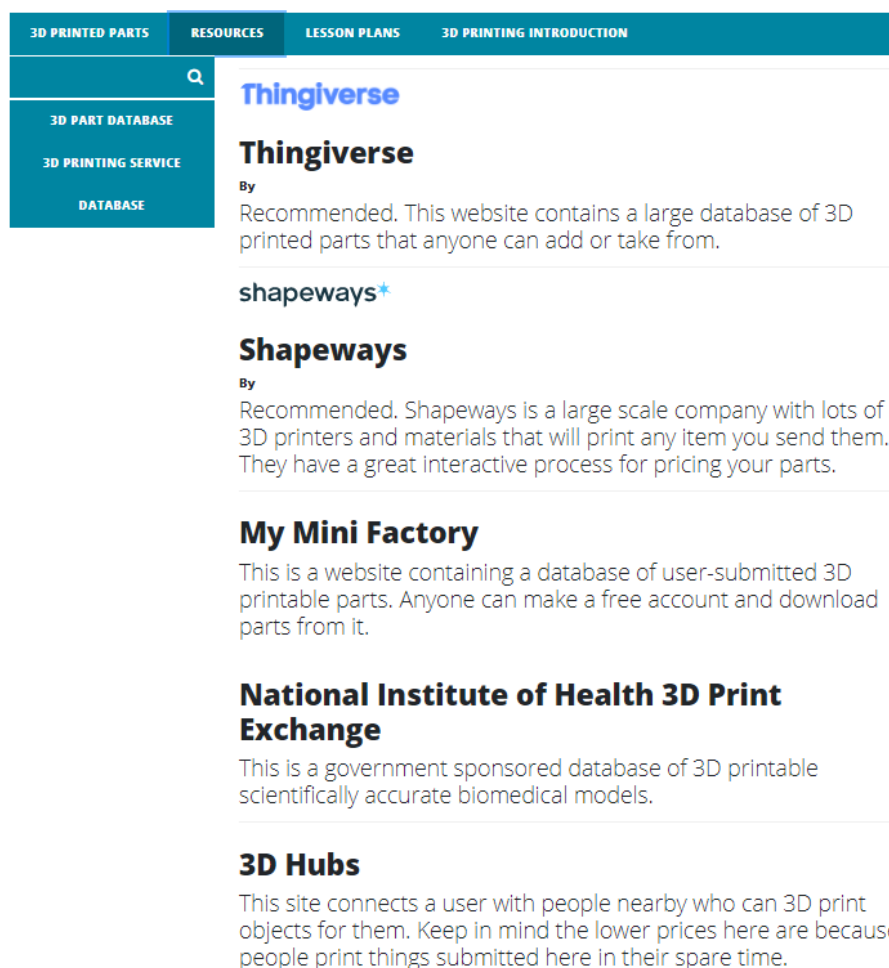


Figure 22. Compendium to help chemistry teachers find 3D printable parts and resources. Teachers can use the four buttons at the top to select different sections of “Resources” and use the bar on the left side to select sub categories.



3D PRINTED PARTS RESOURCES LESSON PLANS 3D PRINTING INTRODUCTION

3D PART DATABASE
3D PRINTING SERVICE
DATABASE

Thingiverse

Thingiverse

By
Recommended. This website contains a large database of 3D printed parts that anyone can add or take from.

shapeways*

Shapeways

By
Recommended. Shapeways is a large scale company with lots of 3D printers and materials that will print any item you send them. They have a great interactive process for pricing your parts.

My Mini Factory

This is a website containing a database of user-submitted 3D printable parts. Anyone can make a free account and download parts from it.

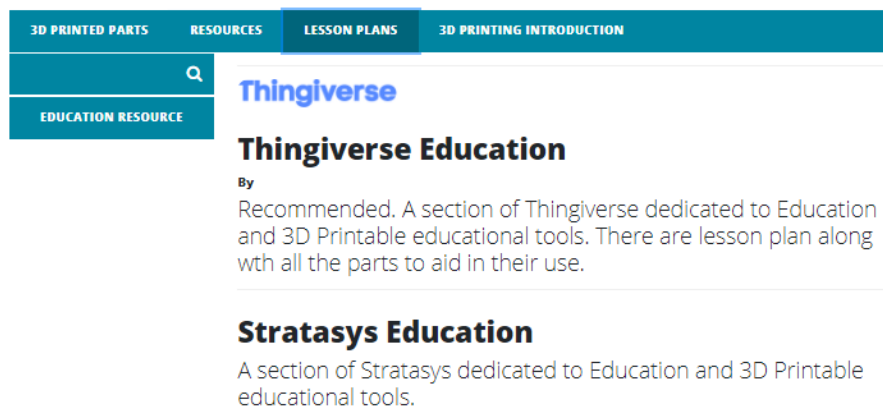
National Institute of Health 3D Print Exchange

This is a government sponsored database of 3D printable scientifically accurate biomedical models.

3D Hubs

This site connects a user with people nearby who can 3D print objects for them. Keep in mind the lower prices here are because people print things submitted here in their spare time.

Figure 23. “Resources” subsection of the compendium. Contains resources which can be used to find 3D printable parts, 3rd party printing companies, and popular 3D printers.



3D PRINTED PARTS RESOURCES LESSON PLANS 3D PRINTING INTRODUCTION

EDUCATION RESOURCE

Thingiverse

Thingiverse Education

By
Recommended. A section of Thingiverse dedicated to Education and 3D Printable educational tools. There are lesson plan along with all the parts to aid in their use.

Stratasys Education

A section of Stratasys dedicated to Education and 3D Printable educational tools.

Figure 24. “Lesson plans” subsection of the compendium. Contains lesson plans which can be used to teach students how to 3D print.

3D PRINTED PARTS
RESOURCES
LESSON PLANS
3D PRINTING INTRODUCTION

TEACHER RESOURCE

The Free Beginner's Guide

By 3DPI

Recommended. 3DPI's Beginner's Guide to 3D Printing. This guide is for anyone looking to learn about the history, background, and application of all things 3D printing.

A Guide to Slicing

By

Recommended. A guide to the common settings used when slicing a part and what each setting does.

Available Slicers

A list of the available slicers, their cost, freatures, and what audience they target.

How to Print: Beginner's Guide To 3d Printing

The aim of this guide is to teach you the fundamental concepts of how to 3D print, and provide you with the tools and resources you need to get started and make an informed choice about buying your first 3D printer.

What is 3D printing?

An introductory guide to 3D Printing from 3DPrinting.com. This contains a list of types of 3D printers, some services, and terminology.

Figure 25. “3D printing Introduction” subsection of the compendium. Contains resources like beginner’s guides to 3D printing, modeling guides, and advanced slicing guides.

Table 10 shows the distribution of resources within the compendium on the Resources page. Relevant to chemistry education, we curated 52 chemistry related 3D printable parts, 10 websites of helpful 3D printing websites, 2 websites of lesson plans for incorporating 3D printing into classrooms, and 10 additional guides to get started with 3D printing. The 74 total resources in our compendium was a much more manageable number than the hundreds of thousands of results found when searching Google. The big advantage for chemistry educators was that we examined many Google results and collected the most relevant. Teachers can now spend more time focusing on using the tools and assets we collected rather than searching through pages of Google results or being confused about where to find relevant information.

Table 10. Distribution of items in compendium of resources.

Category	Items
3D Printed Parts	Total: 52 parts <ul style="list-style-type: none"> ● Potential Energy: 2 parts ● Ionic Bonding: 3 parts ● Molecular Structure: 11 parts ● Nuclear Chemistry: 1 part ● Periodic Trends: 1 part ● Biology: 8 parts ● Atomic Orbitals: 1 part ● Lab Equipment: 20 parts ● Organic Chemistry: 1 part ● Atomic Structure: 1 part ● Anatomy: 3 parts
Resources	Total: 10 websites <ul style="list-style-type: none"> ● 3D Part Databases: 3 websites ● 3D Printing Services: 5 websites ● Databases: 2 websites
Lesson Plans	Total: 2 websites
3D Printing Introduction	Total: 10 guides

In the course of our background research, we identified many common misconceptions and difficulties students have in chemistry, found on the “Chemistry Misconceptions” page, which can be found in Section 2.2. For many of these misconceptions, 3D printed tools exist that could address them. However, for some of the topics that didn’t have 3D printed tools, we found software simulations relevant to the topic. We also discovered PhET: a large online resource with chemistry simulations, run by the University of Colorado, Boulder.⁸⁰ Much like many of the tools we collected in our compendium, this resource was extremely helpful. We linked to many of these simulations as well as 3D printable tools into groups on our website based on the chemistry topic they helped address. We decided to group these simulations based off the organization of the Massachusetts Physical Science Standards for High School Chemistry, the same grouping we used to organize the misconceptions we had found in our research.⁸¹ Each grouping includes the misconceptions and the simulations and 3D printable tools that will best address the misconception in question. A view of the list of misconceptions is shown below in Figure 26 and the complete list is shown in Tables 11-13. When a visitor clicked on a particular misconception, the misconception expanded with more details as well as the tools or simulations useful for addressing the misconception or concept.

⁸⁰ <https://phet.colorado.edu/en/simulations>

⁸¹ 2016 Massachusetts Science and Technology/Engineering Curriculum Framework 2016. Massachusetts Department of Elementary and Secondary Education.

Common Misconceptions

Below we have personally compiled a list of the most common misconceptions that chemistry students struggle with. Each section includes a list of these misconceptions, as well as a small guide on how to explain it. This may include the use of 3D printed tools, lesson plans, and online simulations.

Matter and its Interactions

(Click to Expand)

Students think molecules change size/shape with pressure or temperature changes

Students think identical molecules can vary in size

Students think molecules in different phases have different weights

Students think atomic radii depends solely on number of protons

Students think unbalanced chemical equations exist.

Description:

Students lack the general knowledge of stoichiometry and how to balance equations. I.e. they do not recognize "2H₂" as two sets of diatomic Hydrogen atoms, but rather, four singular Hydrogen atoms.

Recommendation:

Have the students use molecular modeling kits to perform reactions to prove to them that unbalanced chemical equations cannot exist.

- [3D Printable Molecular Modeling Set](#)

As a supplement or in addition too, the simulations below can help.

- [Balancing Chemical Equations](#)
- [Product and Leftovers](#)

Students think when a reaction reaches equilibrium, the system stops reacting.

Students have trouble identifying what is oxidized and reduced in redox reactions.

Students think reactant and product concentrations are equal at equilibrium

Determining the effect of Le Chatelier's Principle on equilibrium

Students have trouble distinguishing between reaction rate and equilibria

Motion and Stability: Forces and Interactions

(Click to Expand)

Students think atoms only have 1 stable electron state

Students think ions in solutions are still connected

Students think there are only 2 types of bonding: ionic and covalent

Students don't understand the effect of different bond types (e.g. double, triple bonds) on shape

2D to 3D representation of molecules

Figure 26. List of common chemistry misconceptions from website page. Visitors click a misconception to get tools and resources to help address that misconception.

As seen in Tables 11-13, each misconception is paired with solutions that are either 3D printable tools (if they were available) as well as online simulations from PhET. For example, for the misconception “Students have trouble determining the effect of Le Chatelier's Principle on equilibrium” in Table 11, there were no 3D printed tools available, but there existed several online simulations that help address the misconception. Another example is the misconception “Students think there are only 2 types of bonding: ionic and covalent” from Table 12. For this misconception, no simulations exist, but we developed a 3D printable tool for this misconception, so it is listed as an aid for the misconception. In total, we detailed 21 major misconceptions and provided 42 tools or simulations to address them. The collection of all this information in one location helped chemistry teachers with resolving the misconceptions without spending much time looking for solutions.

Table 11. “Matter and its Interactions” misconceptions and solutions from our website

Misconception	Solution
Students think molecules change size/shape with pressure or temperature changes	Use a computer simulation like the ones below to alleviate issues. Have the students play with different scenarios and have them visually see what happens when the pressure changes. https://phet.colorado.edu/en/simulation/legacy/gas-properties https://phet.colorado.edu/en/simulation/states-of-matter
Students think identical molecules can vary in size	Use the tool we developed https://www.thingiverse.com/thing:2800605 or use molecular modeling kits and have the students build the molecules and have them try to build two of the same molecules that are different sizes. https://www.thingiverse.com/thing:334917 Alternatively use this simulation instead. https://phet.colorado.edu/en/simulation/legacy/build-a-molecule
Students think molecules in different phases have different weights	Use a simulation tool to help the students visualize what happens before and after a phase change. https://phet.colorado.edu/en/simulation/legacy/balloons-and-buoyancy https://phet.colorado.edu/en/simulation/states-of-matter
Students think atomic radii depends solely on number of protons	Use a simulation to let the students interactively figure out that the electron repulsion is another factor in atomic radii beyond just the nucleus size. On the bottom right check cloud to show increasing size as you add electrons. https://phet.colorado.edu/en/simulation/build-an-atom
Students think unbalanced chemical equations exist.	Have the students use molecular modeling kits to perform reactions to prove to them that unbalanced chemical equations cannot exist. https://www.thingiverse.com/thing:334917

	<p>As a supplement or in addition too, the simulations below can help.</p> <p>https://phet.colorado.edu/en/simulation/balancing-chemical-equations</p> <p>https://phet.colorado.edu/en/simulation/reactants-products-and-leftovers</p>
Students think when a reaction reaches equilibrium, the system stops reacting.	<p>Use simulations to help students visualize how reactions actually occur at the atomic level.</p> <p>https://phet.colorado.edu/en/simulation/legacy/reactions-and-rates</p> <p>https://phet.colorado.edu/en/simulation/legacy/reversible-reactions</p>
Students have trouble identifying what is oxidized and reduced in redox reactions.	<p>We have not found any good tools or simulations to help with this issue. The recommended solution is just to cover more examples so the students have a better baseline from which to make judgements.</p> <p>If covering electrochemistry, this simulation can be used to show how oxidation and reduction are used to generate voltage.</p> <p>https://phet.colorado.edu/en/simulation/legacy/battery-voltage</p>
Students think reactant and product concentrations are equal at equilibrium	<p>Use simulations to help students visualize what is happening.</p> <p>https://phet.colorado.edu/en/simulation/legacy/reactions-and-rates</p> <p>https://phet.colorado.edu/en/simulation/legacy/reversible-reactions</p>
Determining the effect of Le Chatelier's Principle on equilibrium	<p>Use simulations to help students visualize what is happening.</p> <p>https://phet.colorado.edu/en/simulation/legacy/reactions-and-rates</p> <p>https://phet.colorado.edu/en/simulation/legacy/reversible-reactions</p>
Students have trouble distinguishing between reaction rate and equilibria	<p>Use simulations to help students visualize what is happening.</p> <p>https://phet.colorado.edu/en/simulation/legacy/reactions-and-rates</p> <p>https://phet.colorado.edu/en/simulation/legacy/reversible-reactions</p>

Table 12. Motion and Stability misconceptions and solutions from our website

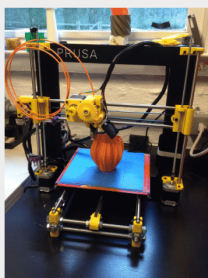
Misconception	Solution
Students think atoms only have 1 stable electron state	Use a simulation to let students explore the stability of atoms in different electron states https://phet.colorado.edu/en/simulation/build-an-atom
Students think ions in solutions are still connected	Use physical models and or illustrations to show students what is happening. Show them that they ions are actually separate and are not sharing anything. https://www.thingiverse.com/thing:1800554
Students think there are only 2 types of bonding: ionic and covalent	We recommend using our visualization tool to explain the concept to students. https://www.thingiverse.com/thing:2800593
Students don't understand the effect of different bond types (e.g. double, triple bonds) on shape	Use physical models or virtual representations to let students play with actual models and experiment with how different bonds change the shape of the molecule https://www.thingiverse.com/thing:334917 Virtual: https://phet.colorado.edu/en/simulation/molecule-shapes https://phet.colorado.edu/en/simulation/legacy/build-a-molecule
2D to 3D representation of molecules	Use physical or virtual molecule building sets to have students practice converting a 2D Lewis structure to a 3D molecule. https://www.thingiverse.com/thing:260226 https://www.thingiverse.com/thing:334917 Virtual: https://phet.colorado.edu/en/simulation/molecule-shapes https://phet.colorado.edu/en/simulation/legacy/build-a-molecule
Students have trouble identifying isomers	Build physical models of isomers and have students identify them. https://www.thingiverse.com/thing:334917 Alternatively, virtual models can be used. Virtual: https://phet.colorado.edu/en/simulation/legacy/build-a-molecule
Students think isomers have different chemical formulas	Build physical models of isomers and have students identify them. Show them how the same atoms go into both isomers https://www.thingiverse.com/thing:334917 Virtual: https://phet.colorado.edu/en/simulation/legacy/build-a-molecule
Students don't	Have students practice building molecules to have them experience

understand how VSEPR predicts bond shape/angles	how VSEPR works https://www.thingiverse.com/thing:334917 Virtual: https://phet.colorado.edu/en/simulation/molecule-shapes
Students don't understand how a Lewis diagram relates to VSEPR	Use a simulation so that students can visualize how the lone pairs and other electron orbitals affect the shape of the molecule. https://phet.colorado.edu/en/simulation/molecule-shapes https://phet.colorado.edu/en/simulation/legacy/build-a-molecule

Table 13. Energy misconceptions and solutions from our website

Misconception	Solution
Students think energy is required in both the forming and breaking of chemical bonds	Use the tool we developed https://www.thingiverse.com/thing:2800582 or use a simulation to show them how energy levels are affected during bonding. https://phet.colorado.edu/en/simulation/atomic-interactions https://phet.colorado.edu/en/simulation/legacy/covalent-bonds
Students think breaking bonds releases energy and forming bonds takes energy	Use the tool we developed https://www.thingiverse.com/thing:2800582 or use a simulation to show them how energy levels are affected during bonding. https://phet.colorado.edu/en/simulation/atomic-interactions https://phet.colorado.edu/en/simulation/legacy/covalent-bonds

After conducting a survey of some chemistry teachers in the local area, we found that many had little to no knowledge of or experience with 3D printing. Therefore, a major barrier to our project's success was disseminating knowledge about how to 3D print tools to the chemistry teachers that we hoped would 3D print tools for their classes. While there were some very detailed and well-made guides available online that we included in our compendium, these were typically rather advanced and difficult for a beginner. Therefore, we made a short, easy-to-understand guide, shown in Figure 27, that would help people who only want to use a 3D printer once or twice, such as chemistry teachers. Our guide was divided into 5 sections, which explain 1) How to set up your 3D printer, 2) How to obtain a 3D printable file, 3) How to set machine settings in your slicing software, 4) How to set the slicing settings in the slicing software, and 5) How to actually print the desired part.



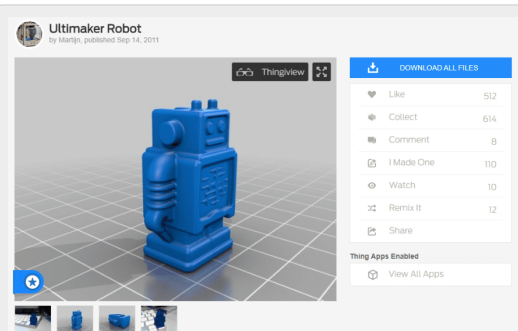
1. Setup. First, find a computer and download Cura from this website: [Cura Software](#). Follow the installation instructions for the software. A 3D printer is also required. Ask a friend or colleague who has one as they probably know how to use it.

There are three important pieces of information you must obtain before continuing: printer model, nozzle size, and material

There are three important pieces of information you must obtain before continuing: printer model, nozzle size, and material diameter.

Nozzle Size will be listed either on the side of the nozzle (the brass piece pointing downwards which extrudes plastic), or in the user manual.

Material Size will be typically listed on the side of the spool or can be measured with calipers.



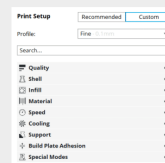
2. Obtain 3D-printable object file. We have created a compendium of printable object files that are relevant to the physical sciences. This compendium can be found on the [database tab](#) at the top of the page.

For additional 3D printable objects, the easiest way to find a part file is by searching on databases of 3D printable part files. One of the most popular ones out there, which is free to use, is [Thingiverse](#). Using this website you can search a very large database for printable object files for free. We recommend using this robot by martin for your first print: [Thingiverse Robot](#)

To download part file(s) from this website click the **DOWNLOAD ALL FILES** button to the right of the picture. This will then download the .stl file(s) that you can load into Cura



3. Set machine settings in Cura. First, open up Cura. It will prompt you to select which printer you will be using. Find yours or the one most similar to yours on the list. Click on the arrow in the top right corner and click add printer, then select yours from the list. Next, click the arrow again and click *Manage Printers*, followed by *Machine Settings*. Here, you will want to change the **Material diameter** and **Nozzle size** for your printer. Once finished, close out of those windows. The last change is to select which material you will be using on the top right. The material diameter and type is usually found on the roll of filament.



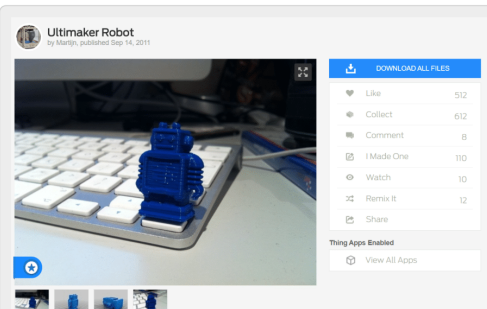
4. Set slicing settings in Cura. To start the editing process, first import your part by clicking *File -> Open File* and then select your file. Once the file is loaded in to Cura, click **Custom** on the upper right side of the screen. Follow the list below, clicking on the tabs indicated. Settings may vary with part size.

Quality: For large parts for which the estimated print time is on the order of hours, the print can be shortened by selecting a larger layer height (0.15-0.2 mm). For smaller parts with finer details, select a finer quality (0.06-0.10 mm). In general, larger layer height reduces print time, but also reduces print quality. We will use 0.1 mm for our robot.

Infill: If you think your part is going to require an appreciable amount of structural integrity, use 100% infill. Otherwise, 30% works great and will print much faster. We will use 10% for our robot.

Support: If your object has parts that overhang, like our robots arms or a bridge, use supports. Otherwise, do not. We will use supports for our robot

Build Plate Adhesion: For parts with small amounts of material touching the base, use build plate adhesion. In general, always use build plate adhesion unless the part is very large. We will be using a brim for our robot.



5. Print the part.

If you aren't printing the part, but rather having someone print the part for you, click the **Save to File** button on the bottom right of the screen. Once the file is saved. Give that file to the person who is printing the part along with the original .stl file(s) you downloaded.

If you are printing the part yourself, first, determine the type of digital media (e.g. SD Card, micro SD, USB drive) required for your 3D printer. Each 3D printer is different, so this section will require you to check your 3D printer's user manual. Once done, you can insert your digital media into your computer and press the **Save to Removable Media** button on the bottom right of the screen. Then, plug in your removable media to the 3D printer. Next, navigate to the part on the printer's interface and click on it to start printing. It is advised that you stay near the printer while the first couple of layers are printed, since this is when errors usually occur. After that, your part should complete successfully! If the part starts off printing incorrectly, it is important to try to stop the print. Consult your user manual to figure out how to do so. If you do not complete successfully, consult your manual or search the web for your problem to find possible solutions.

Congratulations you've printed your first 3D part!

Figure 27. 3D printing guide on the website. Our guide is divided into 5 sections, which explain 1) How to set up your 3D printer, 2) How to obtain a 3D printable file, 3) How to set machine settings in your slicing software, 4) How to set the slicing settings in the slicing software, and 5) How to actually print the desired part.

Our “About” page, seen in Figure 28, contains information on who created the website and why the website exists. Additionally, the page contains a short site map which briefly describes what each link contains. It then links the user to the “Contact Us” page, seen in Figure 28. The “Contact Us” page lists all of the people directly involved with the project and gives the user a way to contact us via email for any questions they may have.

The Why

Chemistry education is fraught with difficult concepts to teach. As a result many students have difficulty with chemistry as a subject. Our goal is to improve the students' understanding of chemistry topics.

The What

This website is an educational resource for teachers who are looking for new ways to combat common difficulty areas in chemistry. This website pulls together many different sources of 3D printing chemistry resources into one location so that finding helpful information is easier.

On the navigation bar at the top:

- **Chem 3D Printing**: Go back to the home page of the website
- **About**: (You are here)
- **3D Printing Guide**: A quick and dirty guide to walk you through printing your first 3D object
- **Chemistry Misconceptions**: A collection of common chemistry misconceptions and some resources (3D printable parts, simulations, etc.) that help address them
- **Search Resources**: A compendium of resources we have collected to help with chemistry education. These resources include 3D part files, 3D printing services, additional 3D printing Guides, and some Lesson Plans

Who we are

We are a group of students and faculty and Worcester Polytechnic University. Contact us by clicking the email button at the bottom of the page or directly at chemiqp@wpi.edu.

Students

- John Stegeman (Junior at WPI)
- Dylan Muise (Junior at WPI)
- Joseph Calnan (Junior at WPI)

Advisors

- Aaron Deskins (Associate Professor of Chemical Engineering)
- Amy Peterson (Assistant Professor of Chemical Engineering)

SEND US AN EMAIL!

The Who

We are a group of students and faculty at Worcester Polytechnic Institute. For more information visit the [contact](#) page.

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Figure 28. About page (left) and Contact Us page (right) on the website.

Throughout the course of our research, we found many resources available online that would be a great help to chemistry education if chemistry teachers could more easily access them. That is what we have tried to facilitate with the creation of this website. Using our website, chemistry teachers would be able to easily find tools or simulations they could use in their classes to help students better understand topics in chemistry. If they happened to find a simulation was available, we provided information about it. Teachers could find parts to print, and if needed, learn how to operate a 3D printer so they could make the part. With all of these components combined into one website, we aimed to create an effective tool to advance chemistry education.

4.6 Website Evaluation Survey Results

4.6.1 Initial Website Evaluation Survey

After completing the website, we designed and sent out a survey in order to determine how easy users could find items in our compendium, 3D printing guide, and chemistry misconceptions pages. The survey was sent out to a diverse group of people comprised of local Worcester high school science educators and WPI students. We aimed to have many different viewpoints and perspectives. In order to understand how easily users could navigate our website, we designed the survey so that it would ask the users to find an item on the website, and then ask them how easy or hard it was to find on a 1 to 5 scale (1-easy to 5-hard), and how long it took them to find the item. At the end of this survey, we asked users general questions about the website quality, how easy it was to find items in general, and whether they would use the website again as a resource. The full survey can be found in Appendix F-1.

When asked to find certain items on the website, users found items in 50 seconds or less on average. Users also said that the items were easy to find, with users giving an overall average rating of 1.86 on a 1 to 5 scale (1-easy to 5-hard). When asked about the overall quality of the website, 8 out of 9 users gave a rating of 4 or 5 with an average of 4.11 (1-bad to 5-great), signifying they liked the quality of the website. However, the results for how easy it was to find items in general were more spread out, signifying that not everyone found the website as easy-to-use as we had expected. Nonetheless, many users said they would use the website as a resource, with 8 out of 9 users rating 4 or 5 with an average of 4.22 on a 1 to 5 scale (1-would not use as a resource to 5-would use as a resource). This survey provided information on how fast users could find information, but it did not provide information on how navigable, or easy to use the website was. We did not evaluate certain aspects of the user experience in this survey, such as the level of frustration the user felt while using the website or asking users what their first impression was about the website. To gather more of this information, we designed a second survey, which is discussed in the following section.

4.6.2 Second Website Evaluation Survey

In order to gauge the quality of our website design, we designed a second survey that would be used to determine how navigable, useful, and easy to use our website is. The survey was sent out to a diverse group of people comprised of local Worcester high school science educators and WPI students. We aimed to have many different viewpoints and perspectives. The goal of this survey was to assess the usefulness and ease of use of the website. The information from the surveys was used to adapt our website based on user experience, as we discuss below. The complete survey can be found in Appendix F-2. The overall conclusions are shown in Table 14 below, with additional information about how we drew these conclusions in the following text.

Table 14. Summary of User Feedback from Website Evaluation Survey

Feature of the Website	User Feedback
Website Design	Looked good to most visitors
	Visitors thought it was easy to navigate and understand where links went
	Visitors liked the images and general design
Website Content	Visitors liked the information on the website
	Visitors thought it was easy to find information they were looking for on the website
	Visitors wanted more information to be added to the website resources for them to search
	Visitors wanted additional organizational options, like pagination, for the resources

The first page of the survey targets the users' first impressions when entering the website. As seen in Figure 29 in below, the users expressed initial positive thoughts about the layout and appearance. Each of the seven responses indicated a positive users' first impression. When asked what the user liked at first, as seen in Figure 30, users seemed to like the home page layout, as well as our guide resource on the menu bar. Lastly, the user was asked to critique our website. From Figure 31, three out of the seven responses offered no critique, while the others requested more pictures, more color, or commented on disliking the text style. The results in these figures shows that the website has a good design that most visitors like.

What was your first impression when you entered the website?

7 responses

Looks Great!
ok look. like a lot of websites
cool
Pretty cool and professional
Nice Layout
clean
looks cool

Figure 29. List of responses to first impression of website.

Is there anything you immediately notice that stands out to you or is visually appealing?

7 responses

I like the background picture at the top and layout, really visually appealing.
picture at top
the Guide
I like the personalized guide.
Nice picture
The font
i like the picture

Figure 30. List of responses to the initial visual appeal of the website.

Is there anything that you immediately notice that you dislike or would like changed?

7 responses

Too much space between lines
more pictures
text on page gives me a headache
No
Not really
Not Particularly
maybe more color or something

Figure 31. List of responses for initial dislikes of website design.

Figure 32 shows the results for what users expected to be the primary use of the website. Shown in Figure 33, 5 out of 7 thought the website was for education, 4 out of 7 thought the website was for chemistry, and 2 out of 7 thought the website was for 3D printing. Based on these results the majority of visitors could easily tell that the website was designed for chemistry education. Not as many of the visitors initially thought that the website was for 3D printing.

Additional graphics of 3D printing on the landing page might address visitors' perceived notion that this website is not for 3D printing.

What do you think the website is made for?

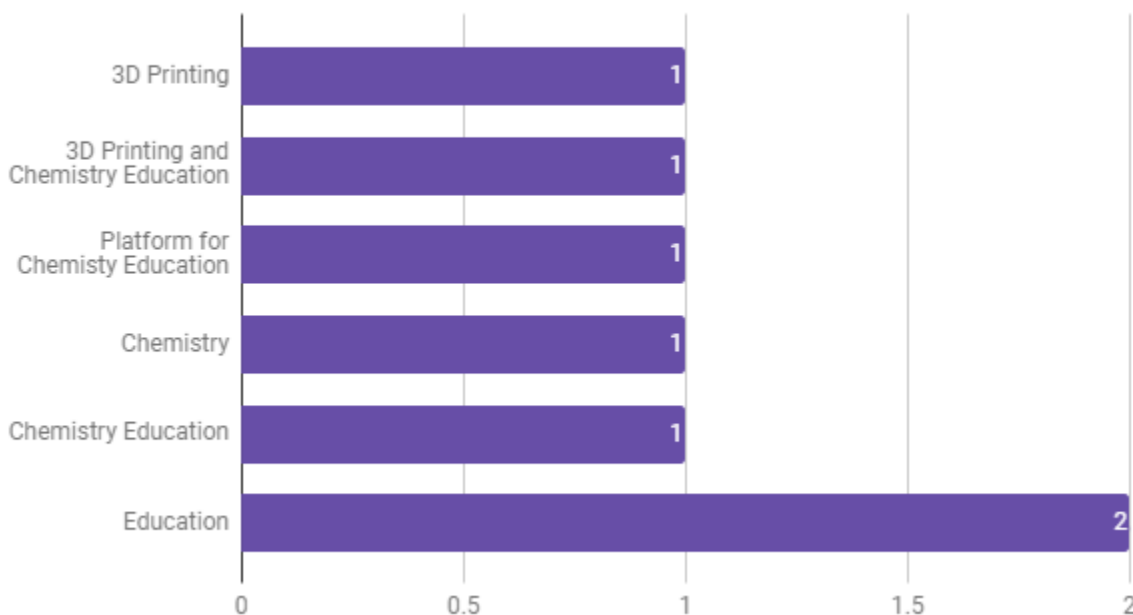


Figure 32. Graph of expected purposes of website.

Shown in below in Figures 33, 34, and 35 are the results concerning the visitors' comments on the navigation bar at the top of every page. Based on the results, the titles for the pages in the navigation bar seemed logical for the visitors. The only slight complaint was that visitors' thought that "Search Resources" would turn into a search bar when clicked, instead of redirecting them to the resources page. These results show that the visitors essentially understand what the links go to, with only minor renaming fixes that we applied to clarify the rest of the confusion.

Did the content after clicking any of the headers surprise you in any way?

7 responses

No, seemed logical
thought guide would be longer
no
No
Nope
Search resources feels like a search bar not a page
I thought search resources was a search bar

Figure 33. List of responses for navigation bar content.

Do you feel that any of the headers could use a different title?

7 responses

Say "Contact Us" instead of "Contact"
not really
no
No really
No
Search resources could just be resources
maybe change search resources to what it actually is.. like resources or soemthing

Figure 34. List of responses for navigation bar titles.

Was there anything confusing or frustrating about how anything was set up.

7 responses

no (3)
"Search Resources" was slow to load
No
No explicit home button
not really

Figure 35. List of responses for website layout confusion.

In Figures 36, 37, 38, and 39, the results concerning our resources page are shown. Figure 30 shows that no visitors thought it was difficult to find any of the three items we asked them to find. Based on the results in Figures 37 and 38, 3 out of 7 visitors liked the search bar and the wide array of information in the resources page. Some visitors, however, thought that the resources page needed more initial organization when first opened, as shown in Figure 39. They thought that pre-organizing the results or adding pages of results instead of one long list would be better. The conclusions we can draw are that in future iterations of the website, additional items should be added to the resources page and pagination should be added. Despite these features missing in the current iteration, most visitors thought that the resources page worked well and was easy to use.

Was it hard to find the items listed above, or something that interests you?

7 responses

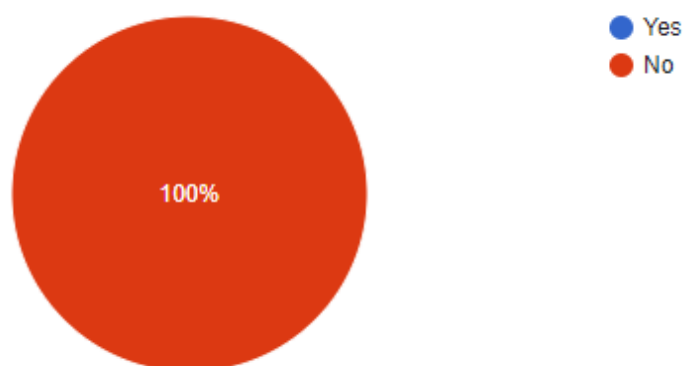


Figure 36. Graph of if visitors felt it was hard to find resources.

What is something you like about this page?

7 responses

The Search Bar
search
color
The links take you straight to the sources
Search bar
It seems to have a wide array of material
It has some interesting information

Figure 37. List of responses for what visitors liked for the resources page.

What is the most frustrating thing about this page?

7 responses

Slow to load the search bar
links doesn't open in same page
items intense. Too bright to read
None
One long list
There's really no organization
I thought there would be more stuff

Figure 38. List of responses for what visitors disliked about the resources page.

Is there anything else you would like to add?

7 responses

More tools
export to list
no
No
Pages for results
Categories
the search bar should be next to the four names on top

Figure 39. List of responses for what visitors thought could be added to resources page.

Figures 40, 41, 42, and 43 display the results of questions relating to the users' experience with the website, as well as their rating of the overall quality, and whether the users would use the website as a resource. Figure 40 shows the answers to the users rating the quality of resources on the website, where a score of 1 was bad and a score of 5 was good. On this, 4 out of 7 respondents gave a rating of 4, and 3 out of 7 gave a rating of 5, for a mean score of 4.4. Figure 41 shows how difficult it was for users to find resources on the website, where 1 signified difficult and 5 signified easy. Here, 1 out of 7 gave a rating of 3, or about medium, 3 out of 7 gave a rating of 4, and 3 out of 7 gave a rating of 5, for a mean score of 4.3. Figure 42 shows how frustrated users felt using the website, where a rating of 1 was frustrating and 5 was not frustrating. Here, 4 out of 7 gave a rating of 4, and 3 out of 7 gave a rating of 5, for a mean score of 4.4. Lastly, Figure 43 shows whether users would use this website as a resource, where a rating of 1 means they would not use the website and a rating of 5 means they would use the site as a resource. Once again, 4 out of 7 gave a rating of 4, and 3 out of 7 gave a rating of 5, for a mean score of 4.4.

Rate the overall quality of the website

7 responses

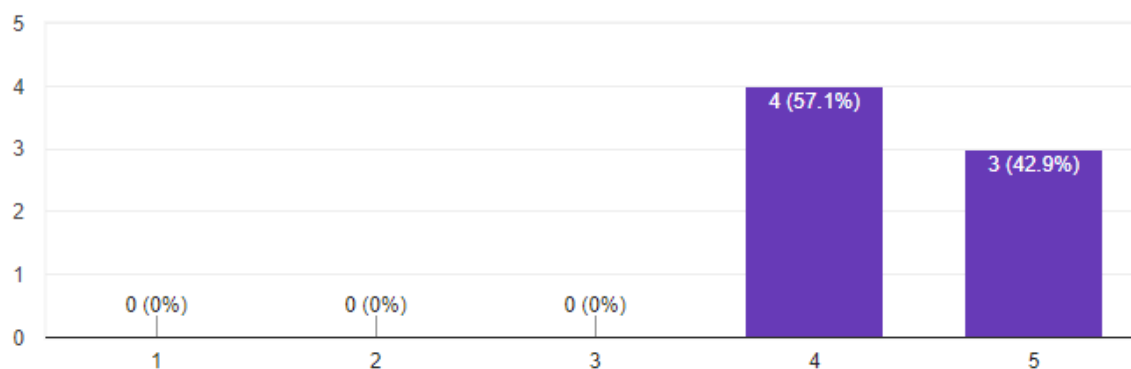


Figure 40. Visitors' rating of quality of resources (1-bad, 5-good)

How easy are things to find on the website?

7 responses

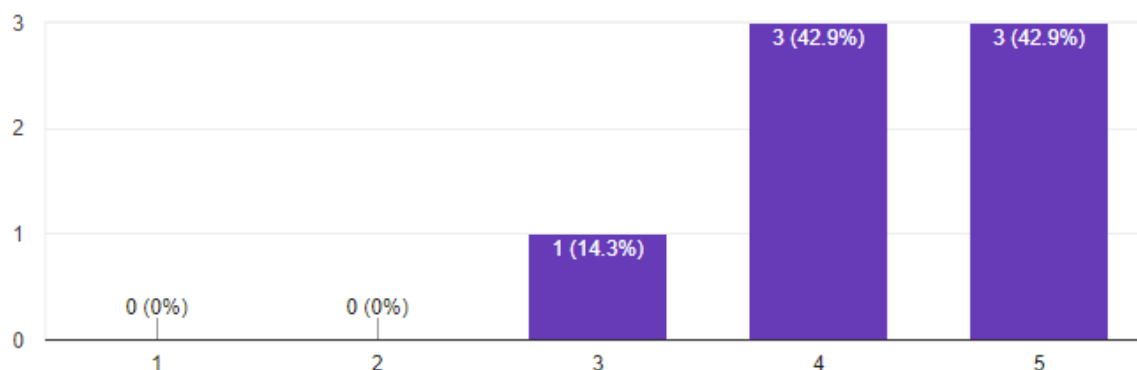


Figure 41. Visitors' rating of difficult of finding resources (1-difficult, 5-easy)

How frustrating was it to use or navigate the website?

7 responses

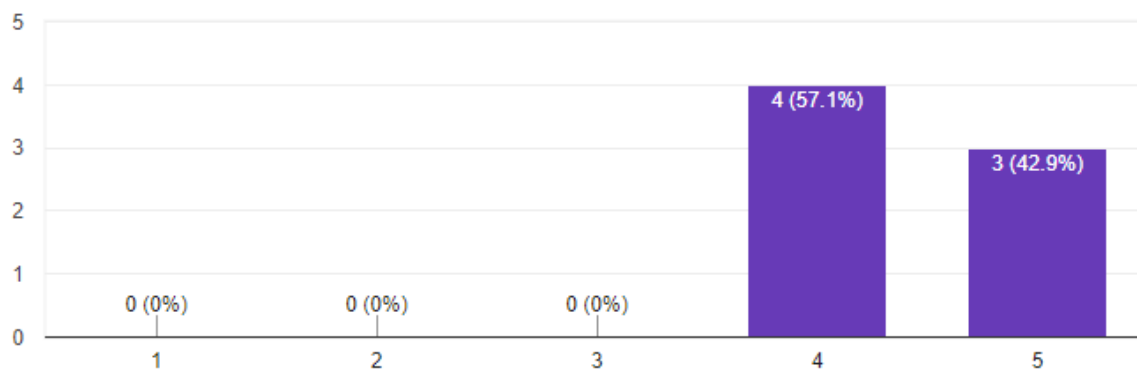


Figure 42. Visitors' rating of how frustrating it was to use website (1-frustrating, 5-not frustrating)

Would you use this website as a resource?

7 responses

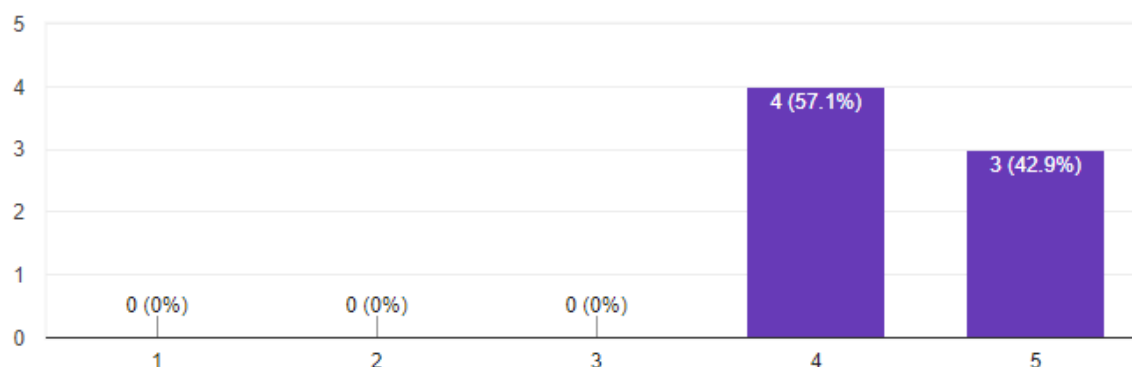


Figure 43. Visitors' rating of if they would use the website as a resource (1-would not use, 5-would use)

These results overall show how useful and easy-to-use the website is for visitors. For overall quality, a mean score of 4.4 shows that, on the whole, visitors are pleased with the website, as seen in Figure 40. More importantly, as seen in Figures 41 and 42, visitors on the whole found it easy to find the resources on the website, as shown by the mean score of 4.3 for the results in Figure 41, and visitors on the whole did not find the site frustrating to use, as shown by the mean score of 4.4 for the results in Figure 42. This is reassuring, since it shows that our site is relatively easy-to-use and not frustrating for visitors, which means the site does not impede visitors from finding information they need. Since these scores are not perfect, we know there is still room for improvement; nonetheless, these results signify we are on the right path. Lastly, as seen in Figure 43, visitors on the whole would return to our site again and use it as a resource, as seen by the mean rating of 4.4 for the results seen in Figure 43. Overall, we can infer from all 4 of these results that visitors find our site overall good, relatively easy-to-use, not too frustrating, and would use the site again as a resource, which are attributes of the website we set out to achieve.

Lastly, we asked our survey respondents for any general feedback about the website. On this question, only 3 of the 7 respondents gave answers, which can be seen in Figure 44 below. One response simply said "No" as their feedback. Another suggested "subcategories for each link," presumably referring to the top menu bar. The final response noted that if this were their field, they "would use it a lot," which seems to suggest the website is a valuable resource, at least to this user.

Any concluding feedback or suggestions you may have?

3 responses

No
Try sub-categories for each link
If this were my field i feel like i would use it a lot

Figure 44. List of visitors' final feedback and comments.

Based on visitor feedback visitors found our website easy to navigate and useful. It was easy to find things and they liked it visually and everyone thought it was a pretty good resource to use. However, some visitors left comments on how to improve the website, so we incorporated some of their suggested changes to the website. The first change was to rearrange the navigation bar and to change some of the labels. In particular, we changed “Contact” to “Contact Us” and “Search Resources” to just “Resources.” We additionally moved “About” to the beginning of the navigation bar so that it wouldn’t be between our “3D Printing Guide” and our “Chemistry Misconceptions” labels. Some of the changes that the visitors suggested, such as adding pagination and additional filters for search results in the resources page. However, this would require a major rewrite of the JavaScript code and could be future work. In summary, the users who took our survey thought it was an accessible website.

4.7 Developing 3D Printable Tools for Chemistry Education

We designed tools to target the specific chemistry misconceptions we researched for which suitable tools were not already available online. We made these tools using SolidWorks Student Edition.⁸² After developing models and converting them to STL files, which are widely recognized by slicers, we sliced them using Cura.⁸³ We then exported the sliced GCode files and printed them on a modified Prusa i3 Hictop edition to ensure that the model printed properly. We evaluated the tools shown below with several chemistry educators, and the additional details of their comments can be found in Section 4.7.4.

4.7.1 3D Phases of Water

One misconception we decided to target was that students think “Identical molecules can vary in size,” found in Table 1 in Section 2.2.1 Matter and Its Interactions. This misconception is related to the different specific volumes of gases and liquids. Since one mole of gas takes up a larger volume than one mole of liquid, students begin to think that gaseous molecules are larger than molecules in the liquid phase. In reality, the larger volume of gases over liquids or solids has to do with the increased kinetic energy of the gas phase, which overcomes any bonding between molecules, and leads to the molecules being far apart from each other. To clarify this point of confusion, we decided to make a display showing the three phases of water using molecules that are the same size. The model will then emphasize the point that the intermolecular bonding and energy of the molecules determines the phases of matter not the size of the molecules.

As seen in Figures 45 and 46, our design shows that, in the solid, liquid, and gas phases of water, molecules are the same size but have different orientations and bonding arrangements. For instance, the vapor phase has three molecules that are spread out in space with weak intermolecular bonding. The liquid water phase has molecules that are closer together but are not packed tightly or organized like the solid phase. the solid phase has molecules that are packed in a tight, crystalline structure with oxygens and hydrogens of adjacent molecules sharing strong intermolecular bonds.⁸⁴

⁸²SolidWorks Student Edition. <http://www.solidworks.com/sw/industries/education/student-edition.htm>

⁸³Cura. <https://ultimaker.com/en/products/ultimaker-cura-software>

⁸⁴Note: Not all forms of ice have a crystalline structure.

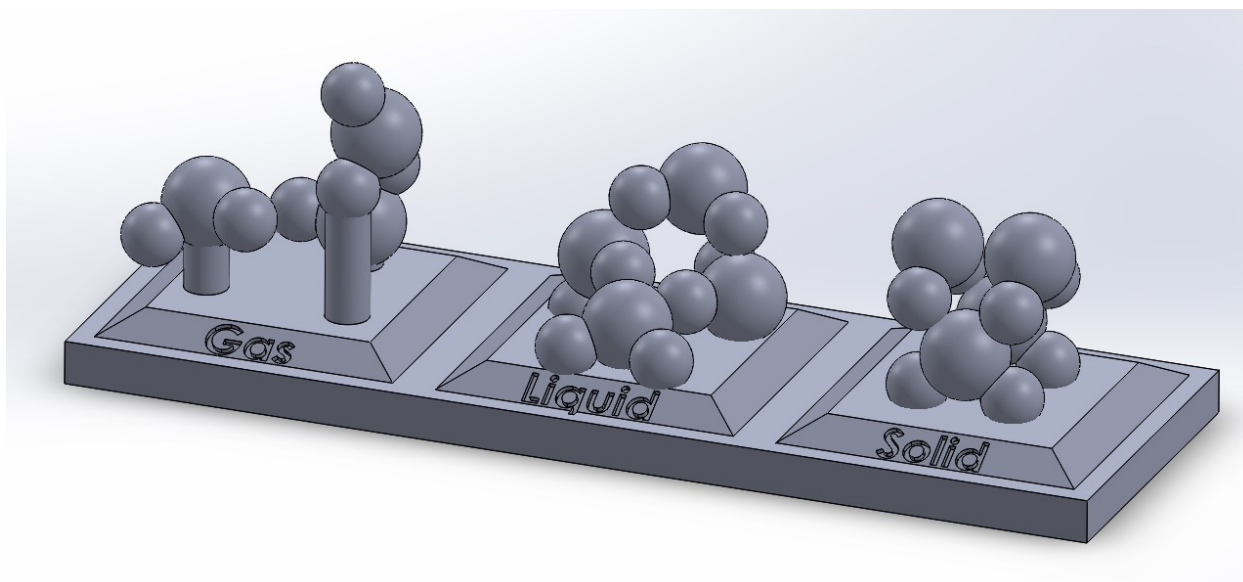


Figure 45. Final SolidWorks design of the water phases tool. This tool shows identical water molecules in different states to address the misconception that molecules can change size or shape in different phases.

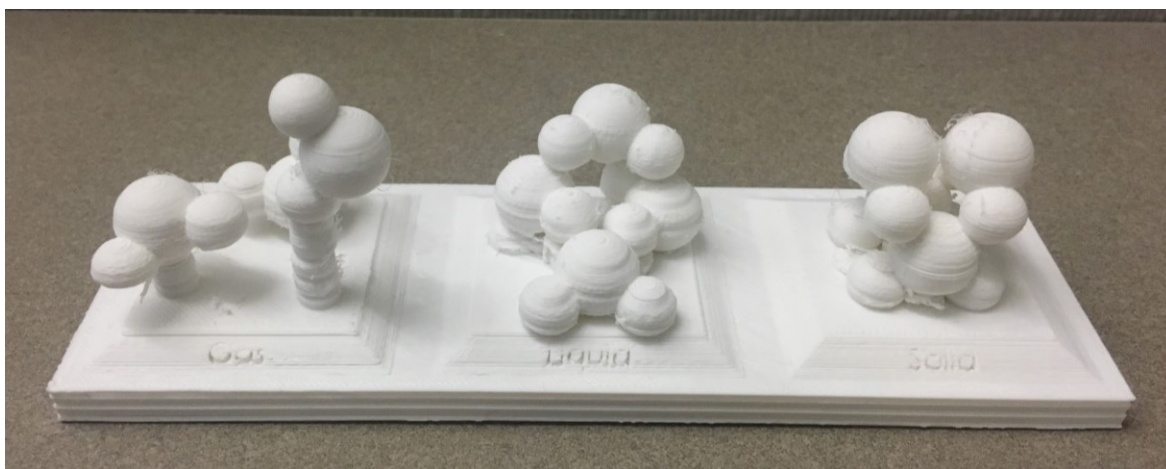


Figure 46. Final water phases tool printed out.

4.7.2 Energy of Bonding

Other misconceptions we addressed through tools we designed were that students think that “Breaking bonds releases energy and forming bonds takes energy,” and that “Energy is required in both the forming and breaking of chemical bonds,” both of which can be found in Table 3 in Section 2.2.3 Energy. Students sometimes misunderstand the role of energy in the creation and destruction of bonds. Table 15 summarizes the misconceptions. In reality, energy is released to form bonds, and is required to break bonds.

Table 15. Breakdown of the misconceptions around energy in bond formation and breaking. The correct statement is shown at the top. The two misconceptions are shown below the correct one.

Misconceptions (Section 2.2.3)	Breaking Bonds	Forming Bonds
Correct Idea	Uses Energy	Releases Energy
Misconception 1	Uses Energy	Uses Energy
Misconception 2	Releases Energy	Uses Energy

To address these points of confusion, we made a tool that demonstrates the change of energy that takes place during bond formation/breaking. Groups of oxygen and hydrogen atoms in two different states of different energy are shown, with a height difference to indicate changing energy, as shown in Figure 47.

As seen in Figures 47, 48, 49, and 50, our tool shows energy as the reaction proceeds, where the x-axis is reaction pathway and the z-axis is energy. The tool addresses the misconceptions revolving around the energy required to break and form bonds by putting molecules and atoms in a reaction at different heights that visually show how much energy is required to be in that state. As seen in Figure 47, the H_2O molecule is lower than the separate H and O atoms. This is meant to show that when an H_2O molecule has its bonds broken, energy is added to the system to make this happen. Conversely, when H and O atoms were to combine into an H_2O molecule, energy would be released and the molecule would become more stable than the individual atoms.

Initially, as seen in Figures 47 and 48, we had individual atoms forming a water molecule, but due to feedback from chemistry teachers in Section 4.7.4, we changed the individual atoms to their diatomic representations to avoid introducing the additional misconception that hydrogen and oxygen can be found as isolated atoms normally. This second version is shown in Figure 49. However, students could become confused with the diatomic versions of H and O forming water. Students may think that the amount of energy required depended solely on the number of bonds. We updated the design by changing to the simple combination reaction of SF_4 and F_2 forming SF_6 shown in Figure 50. This change would show the direct change of a single bond breaking and forming much better while avoiding the misconception that H or O atoms exist independently. On the left side is the higher energy state, showing SF_4 and a F_2 . On the right side is the lower energy state of a molecule of SF_6 . In order for the SF_4 and F_2 to join together to form SF_6 , energy must be used. This tool can be used to demonstrate the concept of bond formation or bond breaking depending on the direction it is looked at. Looking from left to right, the SF_4 and F_2 join together to form a molecule of SF_6 , which is a lower energy state than before; or, from right to left, it would appear that a molecule of SF_6 was broken apart, which required an input of energy to break the bonds between the atoms in the molecule.

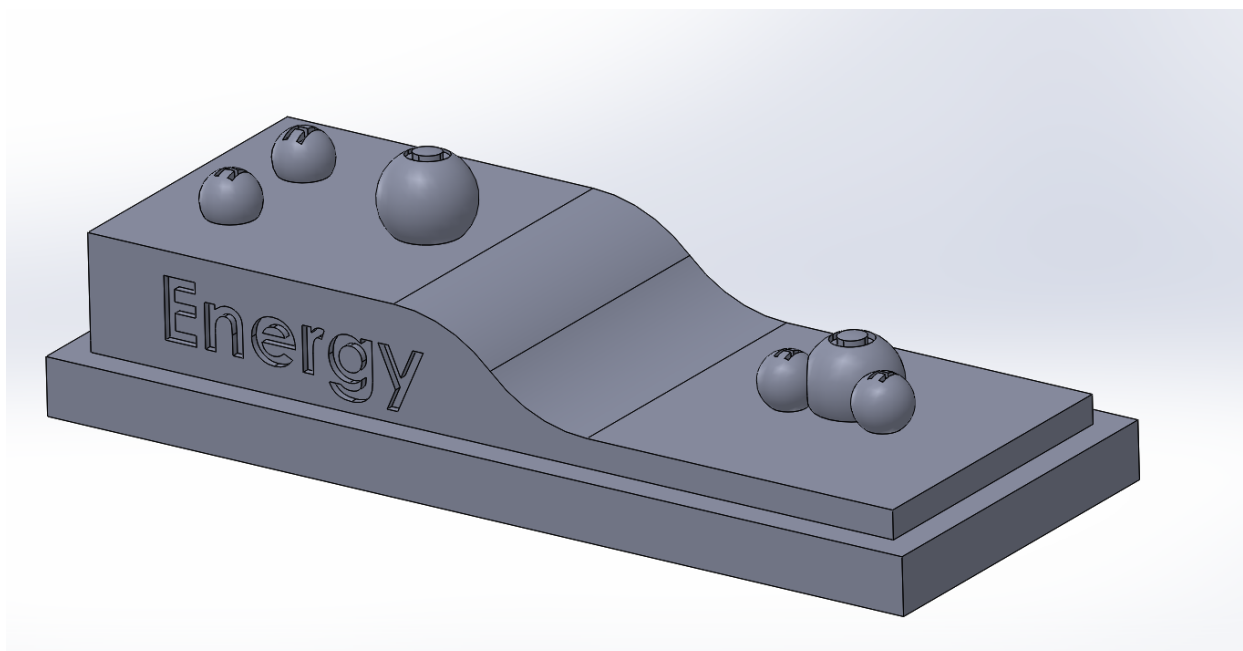


Figure 47. First SolidWorks design of energy tool showing H₂O dissociation. The tool shows that energy is required to split the molecule into atoms and energy is released when the atoms form the molecule.

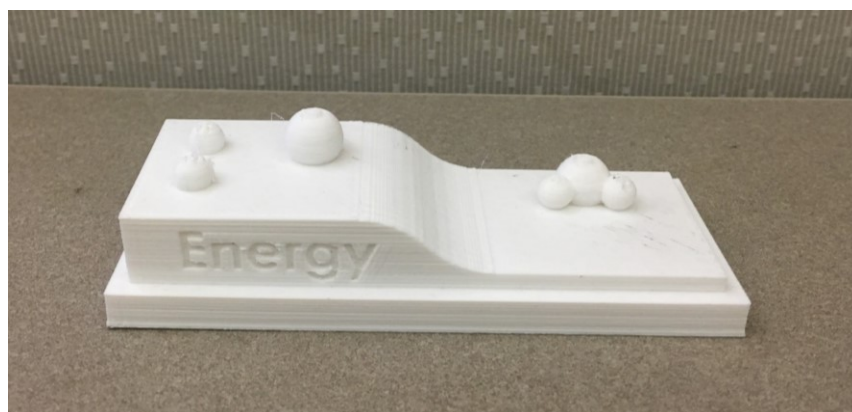


Figure 48. Printed model of energy tool involving H₂O dissociation.

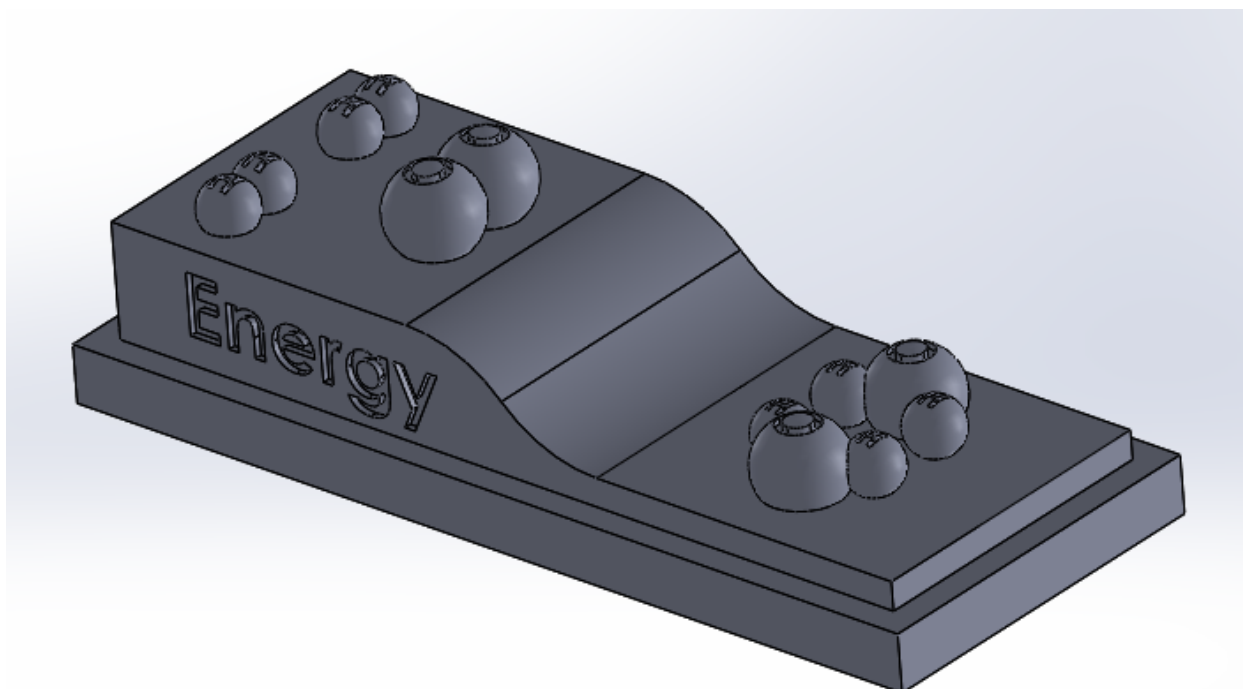


Figure 49. Second model of the energy tool. This version uses diatomic versions of H and O to avoid the misconception that H and O atoms exist naturally by themselves. This version could also help address some student issues with stoichiometry.



Figure 50. Third model of the energy tool with SF_4 and F_2 forming SF_6 . This version avoids multiple bonds breaking and forming. It uses only one bond breaking, and two bond formations to show the concept that energy is released in bond formation and needed to break bonds.

4.7.3 Types of Bonds Tool

Another misconception we targeted was that students think that “There are only 2 types of bonding: ionic and covalent.” However, bonding instead exists on a spectrum depending on the electronegativity difference (ΔEN) of the two atoms in question, ranging from covalent (ΔEN from 0.0 to 0.5), to polar covalent (ΔEN from 0.5 to 2.0), and finally ionic (ΔEN from 2.0 to

3.3)⁸⁵. To clarify this point, we displayed 5 different bonds between atoms in molecules. The atoms are displayed in order of increasing electronegativity difference. The goal of this model was to demonstrate and make clear that there are more than just two types of bonds, but rather a spectrum of them with different strengths based on their electronegativity difference.

As seen in Figures 51, 52, and 53 below, in this part, we labeled the horizontal axis with “Electronegativity Difference,” and labeled each bond with the value of electronegativity difference, as well as labeling the types of bonds (“Covalent,” “Polar Covalent,” and “Ionic”) on the top face of the part, to make it an easy-to-read resource. We decided to use an O-O bond in O₂ ($\Delta\text{EN}=0.0$) for a covalent bond; a C-Cl bond in CCl₄ ($\Delta\text{EN}=0.5$) for a weakly polar covalent bond; an H-O bond in H₂O ($\Delta\text{EN}=1.4$) for a moderately polar bond; an H-Cl bond in HCl ($\Delta\text{EN}=1.9$) for a strongly polar covalent bond; and an Na-Cl bond in NaCl ($\Delta\text{EN}=2.1$) for an ionic bond. Initially as shown in Figures 51 and 52, the text was engraved and put on the base. From feedback from professors Heilman and Brodeur, we revised the design to emboss the text and added a bevel to the base to make the text more readable as seen in Figure 53 and 54.

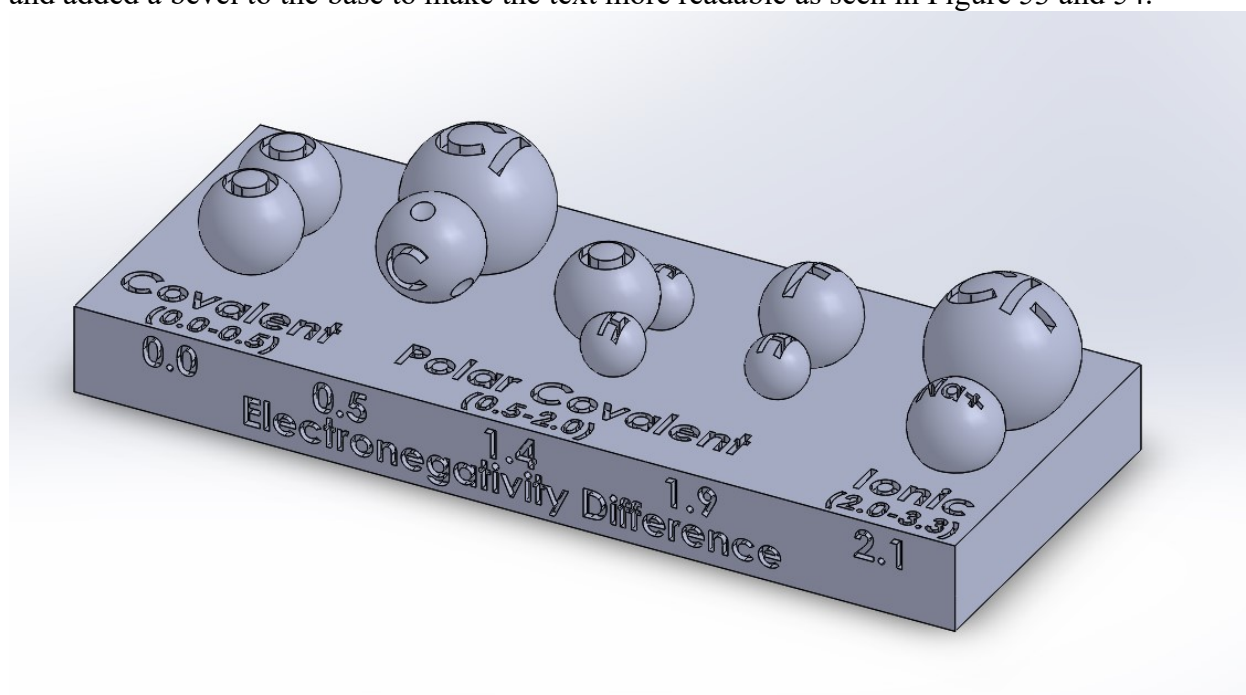


Figure 51. First SolidWorks design for types of bonding tool. This tool is designed to show that there is a scale of bond polarity and all bonds are not purely covalent or ionic to address the misconception that “there are only 2 types of bonding: ionic and covalent.”

⁸⁵ *Electronegativity: Classifying Bond Type*, <http://www.chemteam.info/Bonding/Electroneg-Bond-Polarity.html>, Accessed Feb 12, 2018.



Figure 52. Initial printed model of types of bonding tool

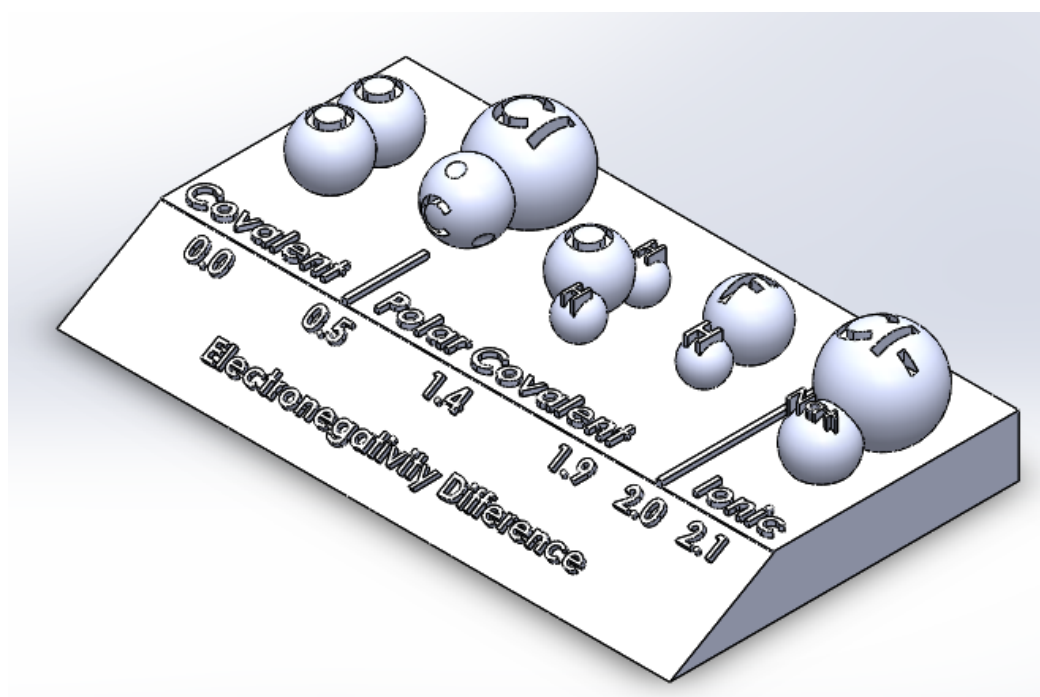


Figure 53. Second iteration of types of bonding tool. This version added a chamfer to the front edge to make the scale more easily visible. Additionally, the text was embossed rather than engraved to make it easier to read.



Figure 54. Printed model of second iteration types of bonding tool.

4.7.4 Feedback from WPI Faculty on 3D Printed Tools

After the initial design phase, we showed our tool designs to faculty at WPI to get their thoughts and feedback on the tools' educational value, as well as to get any suggestions for future redesigns of the tools. In addition to our advisors, Professors Deskins and Peterson, we talked again with Professors Drew Brodeur and Destin Heilman of the WPI Chemistry Department.

Both Professor Brodeur and Professor Heilman were overall pleased with the tool designs, and thought the tools encapsulated their concepts well. With regard to the bond energy tool (Section 4.7.2), both thought it demonstrated the change in potential energy of bond formation well. However, Professor Heilman suggested that it might be more accurate to represent the bond change in the form of a chemical reaction, wherein instead of lone atoms on one side, it would have diatomic forms of hydrogen and oxygen, and on the other side would show two molecules of water, which would demonstrate the chemical reaction $2\text{H}_2 + \text{O}_2 \rightarrow 2\text{H}_2\text{O}$.

When we showed them the bonding tool (Section 4.7.3), they said the tool seemed to have the right idea of how to present the subject matter, but that the tool seemed a bit crowded when printed in real life, and the text was not legible in some cases. To fix this, Professor Brodeur suggested that we make the text pop out of the tool instead of sink in, and to write out

the boundaries of covalent, polar, and ionic on the scale, instead of in parentheses. We also added physical borders between the bonding ranges and increased the size of the model to make it easier to understand.

Professors Brodeur and Heilman also thought the water phases model (Section 4.7.1) clarified the misconception it was designed to target well, although they also had ideas where it could be improved. Professor Heilman noted that our model of ice as purely crystalline wasn't always the case as it can form amorphous structures during rapid cooling, and that our model doesn't entirely capture the difference in density between liquid water and ice. Professor Brodeur pointed out that the spacing in the gas phase was also not quite to scale but understood that the limited size we had to work with made showing a to-scale spacing of the gas phase unfeasible. Both professors also noted that the model would benefit from having more water molecules in each phase display to show more large-scale phenomena of each phase.

Both professors we interviewed were overall pleased with our first iteration prototypes. They expressed where they thought the tools were successful, and also pointed out where they were weaker and could be improved. Their feedback was valuable in developing new iterations of these tool designs, such as shown in Figures 49 and 54.

5. Conclusions and Recommendations

The goal of this project was to improve chemistry education by helping teachers make 3D printed tools that could be used in the classroom to better explain difficult concepts in chemistry. We discuss our overall conclusions and summarize our work. Here we discuss how our project could be further improved, based on data we have obtained from current chemistry teachers, to benefit educators and students alike. We will suggest ways to combat difficulties that our group has encountered, and ways to further expand the project. We also recommend some ways to expand the reach of our project to encompass a broader body of educators, and ways to expand on our work.

5.1 Conclusions and Summary

This project was started with five main objectives in mind:

1. Determine the resources available to teachers to 3D print tools for chemistry education.
2. Compile a directory of 3D printed tools and lesson plans chemistry educators can use to address the students' misconceptions and misunderstandings.
3. Create a feasible delivery method of getting 3D-printed tools to chemistry teachers.
4. Develop a simple to use, and comprehensive guide on how to 3D Print simple objects for use in conjunction with other tools.
5. Develop our own 3D printable tools to target specific misconceptions held by students.

First, we aimed to determine the resources available to teachers to 3D print tools designed to aid in chemistry education through examination of available 3D printing resources and 3D part databases. Through the use of a survey we determined the level of 3D printing knowledge and resources available for local Worcester chemistry teachers. In the survey, we found that most teachers likely had access to a 3D printer, but few knew how to use them. This information suggested that the creation of our guide could help many chemistry teachers start 3D printing objects for the classroom. If the teachers advanced beyond the information in our guide, they could use the compendium on our website to find a plethora of other 3D printing guides with additional information.

Our second goal was to compile a directory of the available 3D printable tools and lesson plans which chemistry educators could use to target specific misconceptions. We created a compendium of chemistry tools that can be printed, shown in Figure 22 of Section 4.5, as well as a simple list of common misconceptions and ways to resolve them shown in Figure 26 in Section 4.5. We collected part files for 3D printed tools relevant to chemistry. These tools can be utilized by chemistry teachers to provide a hands-on explanation of some of the more difficult chemistry topics. These printed objects are portable, interactive, and meant to be passed around the classroom, something not easily done with a computer or text book.

Our third goal was to create a feasible delivery method of getting 3D printed tools to chemistry teachers. We created a website for this: <https://users.wpi.edu/~chem3dprint>. On our website, we placed a compendium of 3D printable tools, a list of tools to target specific

chemistry misconceptions, and a 3D printing guide. Our targeted tools list utilized the misconceptions we researched early on in the project to show how printed physical tools and simulations found online can help explain these misconceptions. Our website also included a start-up guide, shown in Figure 20 in Section 4.5, on which option of getting started in 3D printing is best for the user. This mini-guide directed the user towards asking a friend who owns a 3D printer, using an online service to order parts, or to our guide to teach the user how to 3D print. After initial development of the website, we distributed two surveys to evaluate how navigable, useful, and easy to use the website was. The results of these surveys can be found in Section 4.6. Overall, the surveys showed us that our website has potential to be an invaluable resource to help chemistry educators better explain difficult chemistry concepts.

Our fourth goal was to design a simple 3D printing guide, which people new to 3D printing can use to 3D print their first object. This guide can be used in conjunction with our compendium or list of common misconceptions to print whatever tool an educator may want. Many guides that already exist that discuss 3D printing, but often have excessive information for a first-time user. Our guide was designed specifically for the first-time user, to provide a simple and streamlined approach to start 3D printing.

Our final goal was to develop 3D printable tools to address certain chemistry education misconceptions found from our research. Before we developed any ideas in this field, we first interviewed Professors Drew Brodeur and Destin Heilman of the WPI Chemistry Department to see what chemistry topics they thought would be good opportunities for 3D printed tools. Taking into consideration their ideas, as well as our background research on common chemistry misconceptions and difficulties, we developed three tools. The tools we developed targeted the misconceptions “identical molecules can vary in size,” “breaking bonds releases energy and forming bonds takes energy,” “energy is required in both the forming and breaking of chemical bonds,” and “there are only 2 types of bonding: ionic and covalent.” Upon completion of the tools, we published them on Thingiverse for educators to download and use as well as linked to them from our website.

Our research showed that there are many 3D printable tools and details on the internet that educators can use, but they are dispersed across many online locations. Furthermore, there are many misconceptions and difficult topics in chemistry that could be addressed using 3D printing. Our work found that most teachers had either direct, or indirect access to a 3D printer that they could use, meaning that there is a real possibility of 3D printing being useful in chemistry education. By taking the tools and information we found online, and compiling them all in one place, we have created an all-inclusive website that educators can use to target difficult chemistry concepts with 3D printed tools and improve chemistry education.

5.2 Future Work and Recommendations

Our research provides a substantial starting point for any teams looking to expand on our project. Through the use of surveys, we found that our website was promising, but additional information and objects added to the database could cover additional cases for teachers, as we found via the second website evaluation survey in Section 4.6.2. These cases could cover expanding the resources for organic chemistry or having simpler concepts listed for elementary school chemistry. Future project groups could cover these cases and further our work by focusing their efforts on targeting the misconceptions already outlined in Section 2.2. In particular, the misconceptions concerning equilibrium topics in Table 1 would be the best starting point, as no simulations or tools exist for misconceptions about equilibrium. For example, future project groups could develop an equilibrium “scale” that allows students to interact with it. By adding product or reactant to either side of the scale, the students could see how the system rebalances itself and reestablishes equilibrium. This tool would adequately combat the difficulty many students face of determining the effect of Le Chatelier's Principle on equilibrium, as covered in section 2.2.1. Future project groups could also broaden our project by moving past physical models and focusing on computer models and lesson plans. Possible future work to continue the project includes:

1. Design additional 3D printable tools which can be used to alleviate difficulties in chemistry

Future project groups could continue to develop 3D printable educational tools intended for use in the classroom. Specifically, they could target sections in which a physical model does not already exist, or a significant amount of difficulty does exist. For example, groups could target topics relating to equilibrium, oxidation and reduction, or develop new types of molecular modeling kits. Additionally, lesson plans that are developed with specific 3D printed tools in mind could be created and sent to educators across the country. It would be beneficial to work with local Worcester teachers to determine the best way to implement these lesson plans in the classroom.

2. Increase educator access to 3D printing resources

While the website we created is a great resource for educators, most do not know about it or have access to 3D printers. Future project groups could work with larger companies, like Makerbot or Shapeways, in order to inexpensively put 3D printers into local classrooms. They could also market in order to allow more educators to know about, and subsequently use the website. The feedback from the surveys had suggested that users wanted more performance out of the website, as indicated in section 4.6. In order to add many of the features suggested, more powerful backend servers would be required. These servers would allow us to add features like a script which automatically pulls items from websites like Thingiverse, or a function which lets teachers themselves add resources to the database. Lastly, the compendium could be further refined to add more search options, or even pagination to limit the number of results per page so that it is easier to navigate for the visitors.

3. Research and development of lesson plans and chemistry teaching tools

As well as building new tools as mentioned above, potential groups could also dedicate themselves to the development of a set of lesson plans for the tools to be used in the classroom. Specifically, these groups could bring the tools into local Worcester classrooms to gain user feedback and modify the tools accordingly. Lesson plans could also be developed to assist educators in teaching the misunderstood topics. Lastly, preliminary testing could be performed in order to assess how well the tool and lesson plans combat the specific difficulties in both Worcester high schools and WPI classrooms.

We would recommend that any chemistry educator looking to start using 3D printing in their classroom should start by using our website. From there, they can use our personalized guide to determine the best options for getting 3D printed tools in the classroom. Based on our research, the best option for teachers who do not have access to a 3D printer and will not be printing much is to use a third-party printing service to print limited models for them. The best option for an educator with access to a 3D printer is to use the wealth of resources on our website, and use our 3D printing guide, to print whichever models they would like. Whatever means a teacher chooses, utilizing 3D printed tools in their classroom will help them to better explain difficult topics in chemistry and enhance their students' education.

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Appendices

Appendix A: Chemistry Fundamentals

Chemistry has been a staple in high school education for decades. However, it is also one of the hardest concepts for students to understand. In order for us to figure out what students have issues with we first need a broad overview of the topics typically covered. We will be looking at the 7 core topics listed by the Massachusetts standards above.

Periodicity and the Periodic Table:

Periodicity and the Periodic Table relates to periodic trends, electronegativity, and electron configurations. At the basic level, atoms are made of protons, neutrons, and electrons. Each element is determined by the number of protons it has. For example, all atoms with 6 protons are considered carbon. The number of neutrons an element has can be different, which is called an isotope of the element. Carbon-14 is an example

of an isotope of carbon containing 8 neutrons instead of 6. Each proton gives it a positive charge while each electron offsets this positive charge with a negative charge. The periodic table is organized into three blocks, the s (left two columns), p (right six columns) and d (middle 10 columns). The Periodic Table provides a number of trends that can be seen based on the position of each atom. For example, atom size can be very counterintuitive. Although the nucleus size increases going right on the periodic table, atomic radii decreases due to an increase in charge density as seen in Figure A.1.

Atomic Structure and Bonding:

Atomic structure and Bonding is extremely important in being able to visualize how atoms are connected and what they look like. We will be focusing on one of the fundamental

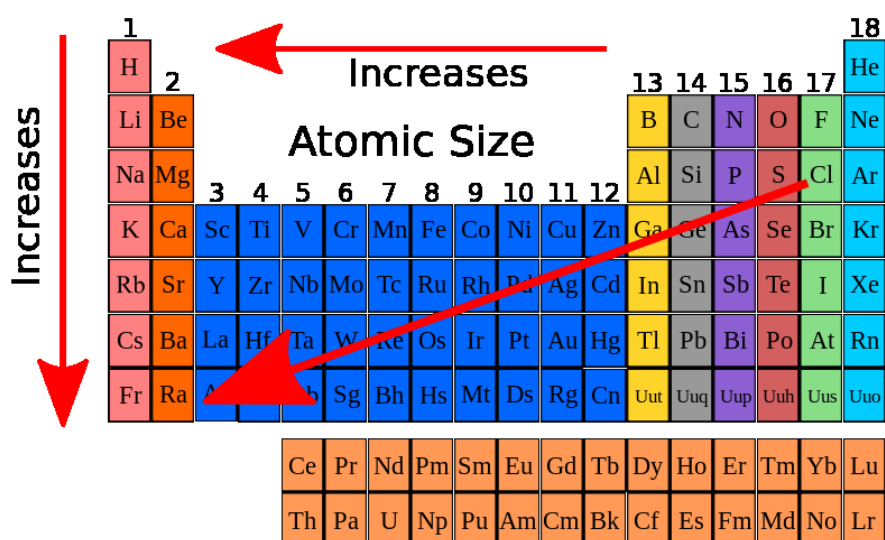


















Figure A.1. Atomic radius trend on periodic table.
<https://commons.wikimedia.org/> under [CC BY 2.0 by Creative Commons](https://creativecommons.org/licenses/by/2.0/)

bonds, the covalent bond⁸⁶. This bond appears in 3 types, the single, double, and triple bond. Bond order is directly proportional to bond strength. We can use these bond orders to determine the shape of a molecule using a proven model. The Valence Shell Electron Pair Repulsion Model (VSEPR Model), as seen in Figure A.2, is a model used to predict the molecular geometry of a compound in solution⁸⁷. It has proven to be exceedingly accurate to determine the geometry of many molecules. VSEPR, above all else, has been traditionally taught alongside the use of model kits.

The VSEPR Model

TABLE 9.2 Common molecular geometries for species with two to six bonded atoms^a

AB _n Notation	AB ₂	AB ₂	AB ₃	AB ₃
Geometry	Linear	Bent (V-shaped)	Trigonal planar	Trigonal pyramidal
				
				
Idealized Bond Angles	180°	<180°	120°	<120°
AB _n Notation	AB ₄	AB ₄	AB ₅	AB ₆
Geometry	Square planar	Tetrahedral	Trigonal bipyramidal	Octahedral
				
				
Idealized Bond Angles	90°	109.5°	90°, 120°	90°

^a Lone pairs are shown using a dashed line.

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Figure A.2. VSEPR bond angle predictions. <https://commons.wikimedia.org/> under [CC BY 2.0 by Creative Commons](#)

Properties of Matter:

The properties of matter are separated into two categories; intensive and extensive properties. Intensive properties are independent of the amount present, while extensive properties directly relate to the amount of matter⁸⁸. Intensive properties are density, color, conductivity, malleability, and luster. While extensive properties are mass and volume. However, it is

⁸⁶https://chem.libretexts.org/Core/Physical_and_Theoretical_Chemistry/Chemical_Bonding/Fundamentals_of_Chemical_Bonding/Bond_Order_and_Lengths

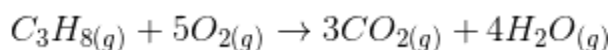
⁸⁷https://chem.libretexts.org/LibreTexts/Mount_Royal_University/Chem_1201/Unit_4%3A_Chemical_Bonding_II_-_Advanced_Bonding_Theories/4.02%3A_The_VSEPR_Model

⁸⁸https://chem.libretexts.org/Core/Inorganic_Chemistry/Chemical_Reactions/Properties_of_Matter

important not to be confused between the properties of an atom and the properties of a substance made up of that atom. Although a substance may be bent into a shape, the individual atom will retain its structure. There are also two types of changes matter can undergo; physical and chemical⁸⁹. A physical change is one that the core makeup of the molecule does not change, for example, phase changes like ice melting into water $H_2O_{(s)} \rightarrow H_2O_{(l)}$. A chemical change is one where the chemical makeup of the compound changes, for example, when iron rusts to form ferrous oxide $4Fe_{(s)} + 3O_{2(g)} \rightarrow 2Fe_2O_{3(s)}$.

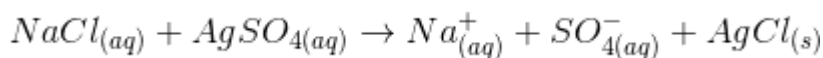
Types of Reactions and Stoichiometry:

Chemical reactions are interactions between chemicals that form new products, release energy, take in energy, change phases, or any combination thereof and more. Chemical reactions have equations that describe their behavior and are always stoichiometrically balanced. Stoichiometry is the balancing of a chemical reaction to make sure ratios are conserved in every



chemical reaction⁹⁰. What follows is a balanced combustion reaction that shows the same number of atoms of each element on each side.

Each and every reaction is stoichiometrically balanced as otherwise the reaction will not occur in the way written. There are a number of different types of chemical reactions that can occur, those being combustion, acid-base, redox, precipitation⁹¹, and nuclear. Acid-base and redox will be covered later in this paper due to the fact that they together encompass the majority of reactions that occur. A combustion reaction is one that when a gaseous hydrocarbon is ignited in the presence of oxygen forms CO₂ and H₂O, as seen above. This reaction is a prime example of what happens inside of an engine of a car. This reaction can however not be complete and produce toxic carbon monoxide gas. Precipitate reactions, otherwise known as double replacement reactions, are reactions where a naturally aqueous cation and anion mix and produce an insoluble compound that precipitates to the bottom. An example of this reaction is as follows: Although sodium chloride and silver sulfate are naturally aqueous in solution, when chloride ion and silver ion connect they produce an insoluble silver chloride compound.



Thermochemistry and States of Matter:

Thermochemistry and states of matter are generally the study of how temperature, pressure, and energy affect matter. Thermochemistry is the study of energy transferred as heat in a chemical

⁸⁹ Ibid.

⁹⁰ https://chem.libretexts.org/Core/Inorganic_Chemistry/Chemical_Reactions/Chemical_Reactions

⁹¹ Ibid.

reaction⁹². This heat can be experimentally and theoretically quantified to be able to tell if a reaction will spontaneously occur or not. Molecules have 3 different phases; solid, liquid, and gaseous. In the solid phase, molecules are in a rigid structure and are difficult to move. In the liquid phase, molecules are free-forming and moving around with ease. In the gaseous phase, molecules have high velocities and are rapidly bouncing off of each other⁹³. You will very commonly see phase diagrams, as seen in Figure A.3, shown with phases as they show how temperature and pressure can affect which phase molecules will be in. These diagrams combined with the ideal gas law, $PV = nRT$ (Pressure, Volume, Moles, Ideal Gas constant, Temperature), are a core component of thermochemistry in the high school classroom.

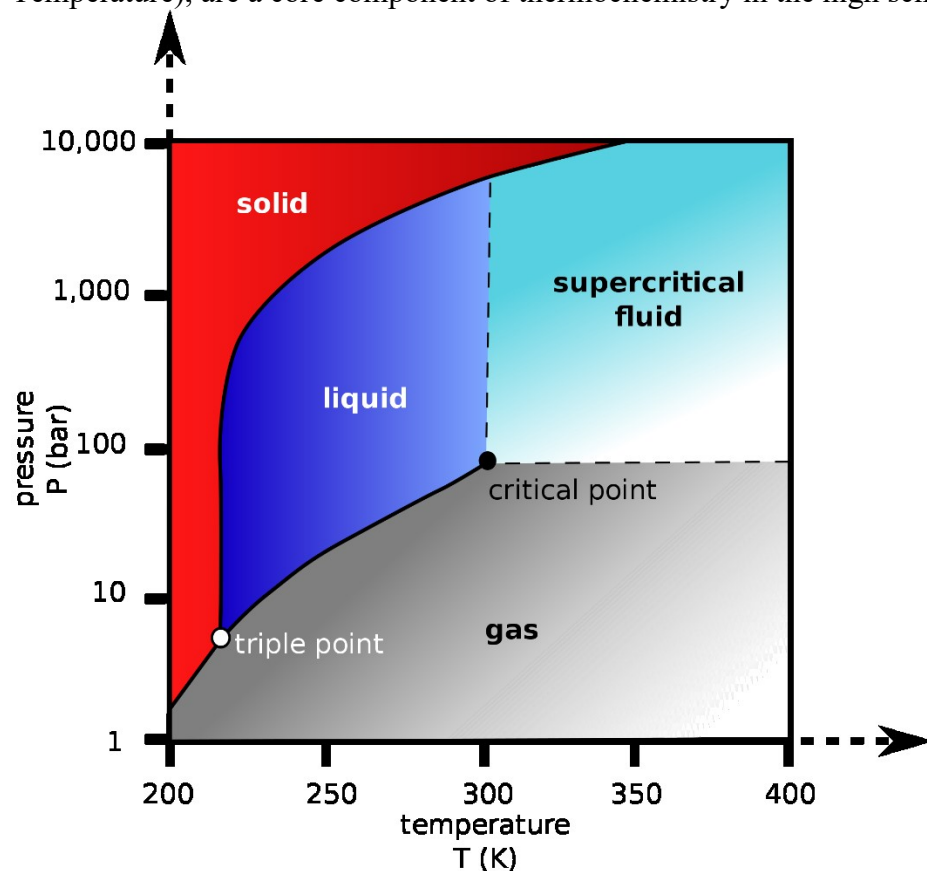


Figure A.3. Phase diagram showing triple point and critical point.
<https://commons.wikimedia.org/> under [CC BY 2.0 by Creative Commons](#)

⁹²[https://chem.libretexts.org/Textbook_Maps/General_Chemistry_Textbook_Maps/Map%3A_ChemPRIME_\(Moor_e_et_al.\)/03Using_Chemical_Equations_in_Calculations/3.05%3A_Thermochemistry](https://chem.libretexts.org/Textbook_Maps/General_Chemistry_Textbook_Maps/Map%3A_ChemPRIME_(Moor_e_et_al.)/03Using_Chemical_Equations_in_Calculations/3.05%3A_Thermochemistry)

⁹³https://chem.libretexts.org/Core/Physical_and_Theoretical_Chemistry/Physical_Properties_of_Matter/States_of_Matter/Phase_Transitions/Phase_Diagrams

Acid-Base Reactions and Equilibrium:

Acid-base and redox reactions cover almost all of the type of chemical reactions that occur. As such, most of chemistry taught at the pre-collegiate level revolves around these concepts. Acid base equilibrium is the study of how acidic and basic molecules act in solution. There are three accepted theories on how acid-base equilibria works; the Arrhenius, Bronsted-Lowry, and Lewis theories. In this paper we will discuss the Lewis theory due to its applicability to more compounds. The Lewis Theory states that acids act as electron pair acceptors, while bases act as electron pair donors⁹⁴. We will look at equilibrium specifically and how it means that there is an ongoing forward-reverse reaction rather than a completion or standstill occurring.

Redox reactions and Electrochemistry:

A redox reaction, or oxidation-reduction reaction, is a reaction in which electrons are transferred between two species resulting in an oxidation of one species and a reduction of the other⁹⁵. In order for it to be considered a redox reaction the oxidation number of the species must change.

⁹⁴https://chem.libretexts.org/Core/Physical_and_Theoretical_Chemistry/Acids_and_Bases/Acid/Overview_of_Acids_and_Bases

⁹⁵https://chem.libretexts.org/Core/Analytical_Chemistry/Electrochemistry/Redox_Chemistry/Oxidation-Reduction_Reactions

Appendix B: Massachusetts Department of Education Physical Science Standards for High School Chemistry

High School Chemistry

The high school chemistry standards build from middle school physical sciences standards. Middle school includes an important transition from macroscopic phenomena to molecular level models that are used to explain and predict energy transformations in phase changes and conservation of matter in chemical changes, including the use of a basic particle model to visualize and represent physical changes of matter. In high school, students consider how structure and composition at sub-atomic scales explain structure-property relationships in chemistry and influence energy transformations and dissipation of energy during chemical and physical changes.

As a discipline that is concerned not only with what we can know but also with what we can do with what we know, chemistry emphasizes **science and engineering practices** related to design and evaluation as well as investigation and modeling. For example, students are challenged to apply chemistry knowledge to designing ways to control the extent of chemical reactions for practical purposes, analyze unknown samples to determine identities and concentrations of possible pollutants, and evaluate the consequences of using different materials for household items. Students are expected to apply mathematical reasoning when considering conservation of matter in chemical reactions and in comparing strength of acid-base solutions. Students apply a variety of science and engineering practices to three disciplinary core ideas of chemistry:

- The major focus of chemistry is on **matter and its interactions**. Students develop both molecular and sub-atomic models of matter and learn to rely on the periodic table as a powerful model for predicting a wide variety of properties of elements and compounds. Students develop greater capacity for building multi-step linear causal explanations by using a combination of the periodic table model and Coulomb's law to predict and explain qualitative comparisons of bond energies. They also consider spatial arrangements of ions in crystal structures and covalent bonds in molecules, and the relative favorability of energy changes required to rearrange components. Students reason about timescales in the context of a collision theory model, and consider how altering external conditions, chemical concentrations, and ways of introducing reactants to a system can be manipulated to control chemical processes. Students refine their understanding of conservation of matter by making quantitative predictions of theoretical yields if reactions are driven to completion using stoichiometric molar proportions and molar mass calculations. They also practice using two major models of reaction processes, the Bronsted-Lowry acid-base reaction model and the oxidation-reduction reaction model, to explain reaction patterns observed in many common phenomena in the natural world.
- Standards for **motion and stability: forces and interactions** help students explain structure-property relationships in terms of forces and interactions, and to consider the energetic stabilities of structures as a driving force in predicting a variety of observable response properties. Water's role as a common solvent is a central example in using molecular-level intermolecular bonding structure arguments to explain the relative solubilities of different ionic compounds. Intermolecular bonding is also explored in rationalizing why some classes of substances are better than others for specific practical uses, and designing molecular level structural specifications of substances that could have desired properties. Students also build on the basic particle model of matter studied in middle school to add quantitative predictions of externally controllable or measurable properties of gases.
- Standards about **energy** help students demonstrate understanding of energy transfer and dissipation of energy in chemical systems. Students rationalize observations of endothermic

and exothermic changes in terms of energy required to break and form chemical bonds when structural rearrangements occur in chemical processes.

PS1. Matter and Its Interactions

HS-PS1-1. Use the periodic table as a model to predict the relative properties of main group elements, including ionization energy and relative sizes of atoms and ions, based on the patterns of electrons in the outermost energy level of each element. Use the patterns of valence electron configurations, core charge, and Coulomb's law to explain and predict general trends in ionization energies, relative sizes of atoms and ions, and reactivity of pure elements.

Clarification Statement:

- Size of ions should be relevant only for predicting strength of ionic bonding.

State Assessment Boundary:

- State assessment will be limited to main group (s and p block) elements.

HS-PS1-2. Use the periodic table model to predict and design simple reactions that result in two main classes of binary compounds, ionic and molecular. Develop an explanation based on given observational data and the electronegativity model about the relative strengths of ionic or covalent bonds.

Clarification Statements:

- Simple reactions include synthesis (combination), decomposition, single displacement, double displacement, and combustion.
- Predictions of reactants and products can be represented using Lewis dot structures, chemical formulas, or physical models.
- Observational data include that binary ionic substances (i.e., substances that have ionic bonds), when pure, are crystalline salts at room temperature (common examples include NaCl, KI, Fe_2O_3); and substances that are liquids and gases at room temperature are usually made of molecules that have covalent bonds (common examples include CO_2 , N_2 , CH_4 , H_2O , C_8H_{18}).

HS-PS1-3. Cite evidence to relate physical properties of substances at the bulk scale to spatial arrangements, movement, and strength of electrostatic forces among ions, small molecules, or regions of large molecules in the substances. Make arguments to account for how compositional and structural differences in molecules result in different types of intermolecular or intramolecular interactions.

Clarification Statements:

- Substances include both pure substances in solid, liquid, gas, and networked forms (such as graphite).
- Examples of bulk properties of substances to compare include melting point and boiling point, density, and vapor pressure.
- Types of intermolecular interactions include dipole-dipole (including hydrogen bonding), ion-dipole, and dispersion forces.

State Assessment Boundary:

- Calculations of vapor pressure by Raoult's law, properties of heterogeneous mixtures, and names and bonding angles in molecular geometries are not expected in state assessment.

HS-PS1-4. Develop a model to illustrate the energy transferred during an exothermic or endothermic chemical reaction based on the bond energy difference between bonds broken (absorption of energy) and bonds formed (release of energy).

Clarification Statement:

- Examples of models may include molecular-level drawings and diagrams of reactions or graphs showing the relative energies of reactants and products.

State Assessment Boundary:

- Calculations using Hess's law are not expected in state assessment.

HS-PS1-5. Construct an explanation based on kinetic molecular theory for why varying conditions influence the rate of a chemical reaction or a dissolving process. Design and test ways to slow down or accelerate rates of processes (chemical reactions or dissolving) by altering various conditions.*

Clarification Statements:

- Explanations should be based on three variables in collision theory: (a) quantity of collisions per unit time, (b) molecular orientation on collision, and (c) energy input needed to induce atomic rearrangements.
- Conditions that affect these three variables include temperature, pressure, concentrations of reactants, agitation, particle size, surface area, and addition of a catalyst.

State Assessment Boundary:

- State assessment will be limited to simple reactions in which there are only two reactants and to specifying the change in only one variable at a time.

HS-PS1-6. Design ways to control the extent of a reaction at equilibrium (relative amount of products to reactants) by altering various conditions using Le Chatelier's principle. Make arguments based on kinetic molecular theory to account for how altering conditions would affect the forward and reverse rates of the reaction until a new equilibrium is established.*

Clarification Statements:

- Conditions that can be altered to affect the extent of a reaction include temperature, pressure, and concentrations of reactants.
- Conditions that can be altered to affect the rates of a reaction include temperature, pressure, concentrations of reactants, agitation, particle size, surface area, and addition of a catalyst.

State Assessment Boundaries:

- Calculations of equilibrium constants or concentrations are not expected in state assessment.
- State assessment will be limited to simple reactions in which there are only two reactants and to specifying the change in only one variable at a time.

HS-PS1-7. Use mathematical representations and provide experimental evidence to support the claim that atoms, and therefore mass, are conserved during a chemical reaction. Use the mole concept and proportional relationships to evaluate the quantities (masses or moles) of specific reactants needed in order to obtain a specific amount of product.

Clarification Statements:

- Mathematical representations include balanced chemical equations that represent the laws of conservation of mass and constant composition (definite proportions), mass-to-mass stoichiometry, and calculations of percent yield.
- Evaluations may involve mass-to-mass stoichiometry and atom economy comparisons, but only for single-step reactions that do not involve complexes.

HS-PS1-9(MA). Relate the strength of an aqueous acidic or basic solution to the extent of an acid or base reacting with water as measured by the hydronium ion concentration (pH) of the solution. Make arguments about the relative strengths of two acids or bases with similar structure and composition.

Clarification Statements:

- Reactions are limited to Arrhenius and Bronsted-Lowry acid-base reaction patterns with monoprotic acids.
- Comparisons of relative strengths of aqueous acid or base solutions made from similar acid or base substances is limited to arguments based on periodic properties of elements, the electronegativity model of electron distribution, empirical dipole moments, and molecular geometry. Acid or base strength

comparisons are limited to homologous series and should include dilution and evaporation of water.

HS-PS1-10(MA). Use an oxidation-reduction reaction model to predict products of reactions given the reactants, and to communicate the reaction models using a representation that shows electron transfer (redox). Use oxidation numbers to account for how electrons are redistributed in redox processes used in devices that generate electricity or systems that prevent corrosion.*

Clarification Statement:

- Reactions are limited to simple oxidation-reduction reactions that do not require hydronium or hydroxide ions to balance half-reactions.

HS-PS1-11(MA). Design strategies to identify and separate the components of a mixture based on relevant chemical and physical properties.

Clarification Statements:

- Emphasis is on compositional and structural features of components of the mixture.
- Strategies can include chromatography, distillation, centrifuging, and precipitation reactions.
- Relevant chemical and physical properties can include melting point, boiling point, conductivity, and density.

[HS-PS1-8 is found in introductory physics.]

PS2. Motion and Stability: Forces and Interactions

HS-PS2-6. Communicate scientific and technical information about the molecular-level structures of polymers, ionic compounds, acids and bases, and metals to justify why these are useful in the functioning of designed materials.*

Clarification Statement:

- Examples could include comparing molecules with simple molecular geometries; analyzing how pharmaceuticals are designed to interact with specific receptors; and considering why electrically conductive materials are often made of metal, household cleaning products often contain ionic compounds to make materials soluble in water, or materials that need to be flexible but durable are made up of polymers.

State Assessment Boundary:

- State assessment will be limited to comparing substances of the same type with one compositional or structural feature different.

HS-PS2-7(MA). Construct a model to explain how ions dissolve in polar solvents (particularly water). Analyze and compare solubility and conductivity data to determine the extent to which different ionic species dissolve.

Clarification Statement:

- Data for comparison should include different concentrations of solutions with the same ionic species, and similar ionic species dissolved in the same amount of water.

HS-PS2-8(MA). Use kinetic molecular theory to compare the strengths of electrostatic forces and the prevalence of interactions that occur between molecules in solids, liquids, and gases. Use the combined gas law to determine changes in pressure, volume, and temperature in gases.

[HS-PS2-1, HS-PS2-2, HS-PS2-3, HS-PS2-4, HS-PS2-5, HS-PS2-9(MA), and HS-PS2-10(MA) are found in introductory physics.]

PS3. Energy

HS-PS3-4b. Provide evidence from informational text or available data to illustrate that the transfer of energy during a chemical reaction in a closed system involves changes in energy dispersal (enthalpy change) and heat content (entropy change) while assuming the overall energy in the system is conserved.

State Assessment Boundary:

- Calculations involving Gibbs free energy are not expected in state assessment.

[HS-PS3-1, HS-PS3-2, HS-PS3-3, HS-PS3-4a, and HS-PS3-5 are found in introductory physics.]

Appendix C: Interview Materials

Summary of Interview with Professor Destin Heilman

Destin Heilman is a Chemistry Professor at WPI. He has taught general chemistry and chaired a committee at the school regarding the state of the general chemistry curriculum and how it could be changed. We interviewed him to gain insight into where he has seen students struggle with in his experience teaching.

Q: What subjects do you find students struggle most with?

A: Stoichiometry, Mole Theory, Geometry, and Acid-Base Equilibrium are subjects that cause students significant trouble.

Q: Do you use any physical representations in class?

A: Standard molecular modeling kits, scaffolding kits to show crystal structure and unit cells, 3D projection system to show molecules.

Next, we began discussing different software packages that he and the school had used in the past. Some software had been used to help with spatial visualization and others were meant to improve learning.

Software, such as MolView that show molecular geometry explicitly, and molecular rotation. Aleks learning software, which teaches students adaptive learning, and helps them stop “algorithmic learning,” or learning “the trick” to answer problems.

Then, Professor Heilman talked about educational changes he had tried implementing at WPI in chemistry labs, and ways to improve chemistry lectures.

At WPI, Project Based Labs have been tried, where students are graded on their attempt to design an experiment, not the results they obtain. This increases engagement with the scientific process.

Demonstrations in lectures using mobile chemical hoods would be more interesting for students in a lecture rather than a lecture on material. Physical learning leads to better retention and is more memorable.

Q: What kind of 3D Printed tools do you think might be beneficial to students?

A: Show molecular forces in water with magnets of different strength (e.g. ferrous and neodymium magnets), so the strong magnets represent molecular bonds, and weaker magnets show secondary or hydrogen bonds. This could also show the movement of

hydrogen between different water molecules, and the constant exchange of hydrogen between hydroxide and hydronium, which leads to acidity or alkalinity in a solution.

Overall, proton transfer is another area where a physical representation would help students understand the topic better.

Transcript of Interview with Drew Brodeur

Audio File: https://drive.google.com/open?id=1Jo57hT5BMVOMp59LAAvhV-hG_48EKraB

Legend:

M - Dylan Muise

B - Drew Brodeur

C - Joe Calnan

S - John Stegeman

[recording begins]

M: We figured first we give you a little brief synopsis of our project. So, we're working on chemistry education specifically and how the use of 3D Printing can help it in high school classrooms. So, we've done a lot of background research on misconceptions and different things students have a lot of trouble within the classroom. So, we're targeting that and trying to find a way that either a 3D printed object or some kind of tool that can be used with 3D printers can help relieve some of the misconceptions, or preferably a whole group of them. So, we actually met with Professor Heilman, one door over and he gave us a lot of interesting information, so we just had a couple of questions we wanted to ask you.

B: Did he focus on biochemistry when he was—

M: A little bit, yeah, and it was really interesting. We are sort of going into those, and, like, anatomy, uh, we found a couple models on organic chemistry, too, so it's not specifically chemistry, but that our main topic. So, really any information from any of the classes you teach would help.

C: So, we usually start with, what subjects in chemistry do you find the most trouble students have. It's a broad question...

B: That's a tough, only because I hear about some in classes that I don't teach, so I can start with those and just go in chronological order. So, starting with Chem 1010, even though we've shuffled around some of the material into 1020 that I am teaching now, a lot of the, pretty much everything involving structure of molecules is in 1010 now, so everything from just atomic structure, the orientation of nucleus and electrons is one issue, and then extend that to electronic structure and excitation of electrons to higher electronic states, that whole idea, and the Balmer Series, and the Rydberg constant, and all electronic transitions, I think students have a hard time with that. But, more broadly, moving from the structure of an atom to molecular structure, 3D visualization of molecules, that's not the most difficult, but it is the one where, whether it's the geometry or orientation of hybrid orbitals on a central atom, or just going from the local geometry around one atom with a certain number of electron groups to the entire structure of even a slightly larger species, more than just one atom with 4 atoms around it,

anything beyond that, I think, even going from each atom to bigger picture is tough. Molecular modeling kits help a lot with that, they're somewhat, I mean, probably the same limitations as you would have on a 3D printed object, or even a set of objects, as a tool, I think would probably be similar to modeling kits that already exist, something that I think it would help with that is much more difficult if not impossible to make physically would be representations of higher principal quantum number orbitals, whether it's molecular orbitals, or atomic orbitals, because you've got something like the 4 f orbitals, or the 3 or 4 p orbitals, even something as simple as the 3 p orbitals, you've got the 2 p that are really easy to visualize because it looks like the dumbbell shape with the node in the middle, but once you go to the higher level, and you have a radial node, to see the difference between the central, same core structure, but then to have a radial node, and then another lobe out here, I think a 3D printed object that had just one dot of plastic holding the outer lobe technically connected to the central lobes, that might not be perfectly visible from outside, but you could still see the shell of that radial node, would be really helpful, and I think that's something a 3D printer could do really well. That's something that I thought of first when I first read your message, because I think everything beyond that for molecular structure is pretty well covered with the tools that available out there, especially with the advances in technology that allow you to do 3D visualization and rotation pretty handily without that much computing power, I think that's pretty well covered, but I think orbital structure, and beyond atomic orbitals, molecular orbitals for something like benzene, or somewhat more complex organic structures, because, last year, we introduced molecular orbital theory into valence bond theory and Lewis structures and VSEPR geometry, so now the students are actually covering molecular orbital theory in depth, but it's one thing to see a few of them in the textbook, it's another thing to work with a molecule that you can actually visualize the bonding, and the anti-bonding orbitals in the same structures, that would be pretty neat, I think. So, that's the first class. For the current class, that no longer deals with any of that, we just deal with stoichiometry, and reactions, and precipitation, thermochemistry and gases, I think a lot of that is traditionally, like, it's a lot of math, but there's not necessarily a physical tool that could help with that, so that's pretty ok. I was thinking about something that could help with the idea of stoichiometry, but again there's plenty of readily available analogies and physical things that you can do to represent the idea of reactions going in certain proportions, that I'm not really sure that a tool is going to represent a great advance in that area, so probably minimal help there. Then you move on to what traditionally are the more difficult areas, like in C Term for Chem 3, which is just weak acid base chemistry, and buffer chemistry, those, there's a lot of visualization to be done about that since it inherently involves principle of equilibrium and reactions, and reversibility of reactions. That's something that I feel animations help with more than one concrete, static device or tool, and maybe that's just 'cause I'm not imaginative enough to think of what such a tool would be to represent the nature of equilibrium. Again, there's a lot of analogies that people can make for chemical reactions and equilibrium and the idea of dynamic equilibrium versus static equilibrium, but--and there are some animations that do help with that. Actually, Professor Heilman worked with someone who was programming something about water in the basement...

M: He told us about that.

B: ...which is helpful but see the difference between that and a static tool.

M: We found a lot of that in our research, that computer animations will help with those subjects, explicitly, a lot better than a tool will.

B: Sure.

M: Professor Heilman actually told us about one lesson, something he did, where he brought in a bunch of Keurig cups, and so, he'd say, 'ok, everyone with this cup, you're a strong acid, everyone with this cup, you're a strong base, and then weak acid and weak base, so, if you're a strong acid, you're trying to get rid of your cup right away, if you're a strong base, you're trying to take protons right away, and weak base you're sort of holding onto it for a little bit, and then sort of giving it away, a bit tentative.' It seemed interesting, but...[laughing]

B: But that could be done with anything, not just K-cups. [laughing]

M: But that's as far as we've found that a physical object will come close to helping that topic.

B: Yes, but the actual, the advantage of having a device or tool like that is in the specific ability to see geometry and spatial orientation, and that can be applied to things like weak acid-base chemistry, to the effect of molecular structure on the strength of acids and bases, which goes back to molecular orbitals and electron density and shifts in electron density. So, I'm less sure that that would be helpful in that arena because the other portions of that course are kinetics, which, again, such a dynamic process that a static thing might not help overly much with that, and then there's more thermodynamics later on, which is just more math. For Chem 1040, which involves electrochemistry, polymer chemistry, and spectroscopy, who knows. I do think that the main application of that could be in learning about--or demonstrating reaction mechanisms, so if you've got, trying to turn what would be a computer generated molecular orbital figure, showing where the electron density is located in a molecule, to highlight to students why, like it's one thing to see a Lewis structure in 2D on paper and say, y'know, this group has 2 double bonded oxygens over here which is why this carbon over here ends up having a partial positive charge. This is where the nucleophilic attack is going to occur, but actually seeing the object with the bubbles of the electron density being pulled, like this is at time equals zero, and then at time greater than zero, it all gets pulled up here leaving a big empty spot down here. That's something--a pretty powerful representation that doesn't require an animation to demonstrate. So, I think, so like the common theme here is, I think, electronic structure and placement, distribution in molecular structures might be one of the more--the target areas for something like this. That's my impression. What else have you guys heard from people, in the past?

M: We've got a--we've also sent out a survey to a lot of high school teachers in the area--we've gotten a lot of responses with VSEPR theory, and just molecular geometry, which is something that's well done with model kits, so our struggle with that is we need to make a more efficient model kit, in terms of less cost, that's tough with 3D printing. We've also got a lot of responses saying that the theory of a mole, like what a mole is, how it's used, a lot of people are saying that that's--we actually didn't have it in our survey, and people are writing it in, that people have an issue with that, so I don't know how we can incorporate that into a design, but--

S: Because you can't print a mole of anything.

B: No!

[inaudible]

S: And you can't really visualize it even with an animation because there's just--it's something you can't understand really.

B: Yup. Yup.

C: Maybe it's confusing that it's like a fundamental constant, people think it exists in some way, well it does exist, like a mole of something exists...

B: Sure.

C: ...but Avogadro's Number is just a conversion factor...

B: You couldn't see a mole of oranges on the table for you to play with, or something like that. It's funny because that, I think that's more of an issue for lower level chemistry courses, because I have not encountered any--well, I don't think I've ever had a single student--maybe one, maybe one each year, out of hundreds will make some comment about, 'I'm just not clear on exactly what this "mole" thing is,' because I think the tools that we have to explain what it is work pretty well.

M: Yeah, we were asking high school teachers specifically...

B: Yeah, if it's the first time that students are hearing about this, and I don't mean to slam any teachers on this, but if it's just not presented effectively, then sure, it has the potential to be super confusing, I totally get that, but again, that's something that's not exactly easily solved with what you're hoping to do.

M: We actually talked a little bit with Professor Heilman, he suggested something that we make--to make intermolecular forces, to demonstrate that, and what we'd do is, we'd take water molecules, and put magnets on, like positive on the oxygen and negative on the hydrogen--it doesn't matter--but it'll show you how, if you put them all in a bin, and take a couple out, they'll stick and stick and stick, and show how it really relates...

B: Absolutely, and you could do that with boring old short- or long-chain hydrocarbons with super weak magnets, and have them be proportionally stronger, and that just goes back to the marbles, from the kids toys, you could make long chains with them, but something like, if you're able to make them large enough, something like to do ions or a dipole, if it would be possible to structure them so that all the poles are on the outside of a spherical ion, and have all the waters align in that way, that could be pretty powerful too, I wasn't thinking about fundamentally altering the substance that you're making, I mean, magnets are cool.

M: Preferably, we wouldn't, because we want it to be as simple as possible, preferably print and done.

B: I do like that idea, though, that is pretty cool. Yeah, but the other things that go beyond fundamental chemistry, I think would, where the applications of the 3D model are high impact, which is in the fields of biochemistry, and higher level organic chemistry where you really are looking for the idea of--he has some in his office, right, active sites of certain proteins, and the local structure of one of those, and why their activity results from the shapes and dimensions of those pockets. That's something where, to go, just to say the words, 'the primary, secondary, tertiary and quaternary structure of proteins,' it doesn't mean much to someone on paper, but then when you see the thing in front of you, you're like, I get it, cool. So, that why it's tough, because I think the maximum impact of what you're hoping to do is not at the lower level chemistry, which is unfortunate, it's a challenge, for sure.

M: That's starting to be something we're starting to find, too, I mean, as we're doing more and more research, we're actually finding a lot of tools that already exist, and we're starting to come to realize that a lot of stuff out there already exists and--so, recently, we've started to build compendium of all the things that we've found, and so, we're thinking that might be a shift in our

project, and it might go towards that way, we create a list, and teachers will come to us to search this list and see if there's anything that they might find useful.

B: Yeah, that's a helpful central source of information, definitely. I'm trying to think through some of the sophomore level stuff that you were all working on, the idea of analytical tools, and the concepts that we have there, but that's a tough one.

M: Do you use any physical models in your class? Besides model kits? Or even model kits, do you use them?

B: Nope. Um, so actually the only other thing that I could think of, which again goes slightly higher level materials, thinking of what I use in class, these random objects that I have, like the bucky ball and soccer balls and tennis balls that I had to use, when you get to the higher level inorganic chemistry, and you focus a lot on molecular symmetry, that's something that's a weakness of molecular models that you can fix by printing something directly. Finding point groups for molecules, which are basically just a label that tell you all the symmetry operations contained within that shape, whatever that object is. That's something where you could print some more complex geometries and structures that model kits can't make, so that's an opportunity there, though again, that's not at the lower level, but does have an application at some level of chemistry education. Looking for some of the higher symmetry groups to get the complexes and the shapes is not really possible with the boring kits that we have here. Basically, the equivalent level of proteins and active sites, but with inorganic complexes, specifically for molecular symmetry, good opportunity there I think.

[end of recording]

Appendix D: IRB Approval

WORCESTER POLYTECHNIC INSTITUTE

Institutional Review Board

Worcester Polytechnic Institute IRB
HHS IRB # 00007374

1 November 2017
IRB File: 18-0100

RE: IRB Application for Exemption File: 18-0100 "3D Printing and Chemistry Education"

Dear Prof. Deskin,

The WPI Institutional Review Committee (IRB) has reviewed the materials submitted in regards to the above mentioned study and has determined that this research is exempt from further IRB review and supervision under 45 CFR 46.101(b): (2) Research involving the use of educational tests (cognitive, diagnostic, aptitude, achievement), survey procedures, interview procedures or observation of public behavior, unless: (i) information obtained is recorded in such a manner that human subjects can be identified, directly or through identifiers linked to the subjects; and (ii) any disclosure of the human subjects' responses outside the research could reasonably place the subjects at risk of criminal or civil liability or be damaging to the subjects' financial standing, employability, or reputation.

This exemption covers any research and data collected under your protocol from 1 November 2017 until 31 October 2018, unless terminated sooner (in writing) by yourself or the WPI IRB. Amendments or changes to the research that might alter this specific exemption must be submitted to the WPI IRB for review and may require a full IRB application in order for the research to continue.

Please contact the undersigned if you have any questions about the terms of this exemption.

Thank you for your cooperation with the WPI IRB.

Sincerely,



Ruth McKeogh
WPI IRB

WPI Institutional Review Board

100 INSTITUTE ROAD, WORCESTER MA 01609 USA

Appendix E: Survey Distributed to Chemistry Educators and Results

1/24/2018

Survey for 3D Printing uses in Chemistry Education

Survey for 3D Printing uses in Chemistry Education

We are a group of WPI students working to identify students' misconceptions and difficulty areas in chemistry. This information will enable us to design a 3D-printed tool that can be used in the classroom to teach difficult concepts more effectively. We have reviewed academic literature to identify some common misconceptions that exist, but we hope to use this survey to identify more specific issues students have in the classroom from teachers firsthand.

This survey was created by us, Joseph Calnan, Dylan Muise, and John Stegeman, and is sponsored by WPI.

For any questions or concerns, please email us at ChemIQP@WPI.edu

This survey is completely anonymous.

1. Check the topics students find most difficult to understand

Check all that apply.

- ☐ Molecular Geometry
- ☐ Types of Bonds
- ☐ Periodic Properties
- ☐ Lewis Structures
- ☐ VSEPR Theory
- ☐ Reduction-Oxidation reactions
- ☐ Acid-Base
- ☐ Nuclear Chemistry
- ☐ Other: _____

2. What other concepts are hard for students to understand?

3. What physical objects or representations (Molecule Modeling Kit, Orbital Models, etc.) do you use in your classroom?

1/24/2018

Survey for 3D Printing uses in Chemistry Education

4. What types of 3D printed objects do you think would be useful for teaching chemistry?

Available 3D printing resources**5. Do you have access to 3D printers where you teach?***Mark only one oval.*

- ☐ Yes
- ☐ No
- ☐ Maybe

6. If you have access to a 3D printer, what kind of printer is it?

7. Have you used a 3D printer before?*Mark only one oval.*

- ☐ Yes
- ☐ No

8. How familiar are you with these 3D printing resources?*Check all that apply.*

	Thingiverse	Shapeways	MakeXYZ	3D Hubs	Protolabs
Unfamiliar	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Heard of it	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Used	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

9. Are there any other 3D printing resources you have heard of or used?

1/24/2018

Survey for 3D Printing uses in Chemistry Education

10. What would you be willing to pay for a 3D printed teaching aid (such as costs to print)?

This includes 3D molecules, molecular building kits or any other related teaching aids.

11. How much time would you be willing to put into printing out and assembling a 3D printed teaching aid?

Final Questions

Basic class demographic information

12. What level of chemistry courses do you teach?*Check all that apply.*

- ☐ General Chemistry
- ☐ Honors Chemistry
- ☐ Advanced Placement (AP) Chemistry
- ☐ Other: _____

13. About how many students do you have in a typical class?*Mark only one oval.*

- ☐ Less than 10
- ☐ 10-20
- ☐ 21-30
- ☐ 31-40
- ☐ 41+

Powered by
 Google Forms

Appendix F: Website Evaluation Surveys

1. Initial Survey

2/24/2018

Website Evaluation Survey

Website Evaluation Survey

We are a group of WPI students working to identify students' misconceptions and difficulty areas in chemistry. We have reviewed academic literature and performed previous surveys to identify some common misconceptions that exist. We used the information to create a website that collects tools and services to help address the misconceptions that we found. This survey is to evaluate the user interface of the website and determine what changes should be made.

This survey was created by us, Joseph Calnan, Dylan Muise, and John Stegeman, and is sponsored by WPI.

For any questions or concerns, please email us at ChemIQP@WPI.edu

This survey is completely anonymous.

How to Start

In a new window, please open the page:

<https://users.wpi.edu/~chem3dprint/>

The survey will consist of a series of questions designed to evaluate how difficult and how long it takes to find specific items. The items may be located on different pages or sections of the website.

Find a model of electron orbitals

1. What did you find?

2. How easy was it to find?
Mark only one oval.

	1	2	3	4	5	
Easy	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Hard

3. How long did it take to find?
Mark only one oval.

- ☐ Less than 30 seconds
☐ 30 seconds to 1 minute
☐ 1 minute to 2 minutes
☐ More than 2 minutes
☐ I did not find it

Find a model of a manual centrifuge

https://docs.google.com/forms/d/1e8Two941LQhHs8tsQpLc7ulqc_ProH2Bi_1kFHPkfGQ/edit

1/6

2/24/2018

Website Evaluation Survey

4. What did you find?

5. How easy was it to find?*Mark only one oval.*

	1	2	3	4	5	
Easy	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Hard

6. How long did it take to find?*Mark only one oval.*

- ☐ Less than 30 seconds
- ☐ 30 seconds to 1 minute
- ☐ 1 minute to 2 minutes
- ☐ More than 2 minutes
- ☐ I did not find it

Find a service that will 3D print parts for you**7. What did you find?**

8. How easy was it to find?*Mark only one oval.*

	1	2	3	4	5	
Easy	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Hard

9. How long did it take to find?*Mark only one oval.*

- ☐ Less than 30 seconds
- ☐ 30 seconds to 1 minute
- ☐ 1 minute to 2 minutes
- ☐ More than 2 minutes
- ☐ I did not find it

Find a website where you can find more 3D printed parts

2/24/2018

Website Evaluation Survey

10. What did you find?

11. How easy was it to find?

Mark only one oval.

	1	2	3	4	5	
Easy	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Hard

12. How long did it take to find?

Mark only one oval.

- ☐ Less than 30 seconds
- ☐ 30 seconds to 1 minute
- ☐ 1 minute to 2 minutes
- ☐ More than 2 minutes
- ☐ I did not find it

Find a teaching tool that targets student misconceptions about atomic radii

13. What did you find?

14. How easy was it to find?

Mark only one oval.

	1	2	3	4	5	
Easy	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Hard

15. How long did it take to find?

Mark only one oval.

- ☐ Less than 30 seconds
- ☐ 30 seconds to 1 minute
- ☐ 1 minute to 2 minutes
- ☐ More than 2 minutes
- ☐ I did not find it

Find a teaching tool that targets student misconceptions about equilibrium

2/24/2018

Website Evaluation Survey

16. What did you find?

17. How easy was it to find?

Mark only one oval.

	1	2	3	4	5	
Easy	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Hard

18. How long did it take to find?

Mark only one oval.

- ☐ Less than 30 seconds
- ☐ 30 seconds to 1 minute
- ☐ 1 minute to 2 minutes
- ☐ More than 2 minutes
- ☐ I did not find it

Find a software that slices 3D part files to 3D print with

19. What did you find?

Please write the software name.

20. How easy was it to find?

Mark only one oval.

	1	2	3	4	5	
Easy	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Hard

21. How long did it take to find?

Mark only one oval.

- ☐ Less than 30 seconds
- ☐ 30 seconds to 1 minute
- ☐ 1 minute to 2 minutes
- ☐ More than 2 minutes
- ☐ I did not find it

Find 4 settings that must be changed when slicing a part for 3D printing

2/24/2018

Website Evaluation Survey

22. What did you find?

Please write all 4 settings found below.

23. How easy was it to find?

Mark only one oval.

	1	2	3	4	5	
Easy	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Hard

24. How long did it take to find?

Mark only one oval.

- ☐ Less than 30 seconds
- ☐ 30 seconds to 1 minute
- ☐ 1 minute to 2 minutes
- ☐ More than 2 minutes
- ☐ I did not find it

Thank you for your time. Please answer these last few questions before you finish.

25. Rate the overall quality of the website

Mark only one oval.

	1	2	3	4	5	
Poor	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Excellent

26. How easy are things to find on the website?

Mark only one oval.

	1	2	3	4	5	
Easy	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Hard

2/24/2018

Website Evaluation Survey

27. Would you use this website as a resource?*Mark only one oval.*

	1	2	3	4	5	
Definitely No	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Definitely Yes

28. Any feedback or suggestions you may have?

Powered by
 Google Forms

2. Second Survey

2/19/2018

Revised Website Evaluation Survey

Revised Website Evaluation Survey

We are a group of WPI students working to identify students' misconceptions and difficulty areas in chemistry. We have reviewed academic literature and performed previous surveys to identify some common misconceptions that exist. We used the information to create a website that collects tools and services to help address the misconceptions that we found. This survey is to evaluate the user interface of the website and determine what changes should be made.

This survey was created by us, Joseph Calnan, Dylan Muise, and John Stegeman, and is sponsored by WPI.

For any questions or concerns, please email us at ChemIQP@WPI.edu

This survey is completely anonymous.

How to Start

In a new window, please open the page:

<https://users.wpi.edu/~chem3dprint/>

The survey will consist of a series of questions designed to evaluate how difficult and how long it takes to find specific items. The items may be located on different pages or sections of the website.

Feel free to browse our website before we get started!

Here, we are looking for some feedback on the layout of our website, its ease of use, and nomenclature or items that do not make much sense.

1. What was your first impression when you entered the website?

2. Is there anything you immediately notice that stands out to you or is visually appealing?

2/19/2018

Revised Website Evaluation Survey

3. Is there anything that you immediately notice that you dislike or would like changed?

Now that you've had a chance to look around...

4. What do you think that this website is meant for?

Click on each of the menu options at the top of the page, and briefly look around to answer the next few questions.

5. Did the content after clicking any of the headers surprise you in any way?

6. Do you feel that any of the headers could use a different title?

7. Was there anything confusing or frustrating about how anything was set up.

Click "Search Resources," and have a look around our database.

Here we have listed many resources our users can take advantage of. Have a look around and click any options that may interest you.

To test the database, you can either look around yourself or try finding these items:

<https://docs.google.com/forms/d/160WWGH6gcL6o3JZmU3A7SvZzAsmYn81C0aj5clssbPY/edit>

2/19/2018

Revised Website Evaluation Survey

A molecular model kit
 Some lesson plans
 A database of 3D printable parts

8. Was it hard to find the items listed above, or something that interests you?

Mark only one oval.

- ☐ Yes
- ☐ No
- ☐ Other: _____

9. What is something you like about this page?

10. What is the most frustrating thing about this page?

11. Is there anything else you would like to add?

Thank you for your time. Please answer these last few questions before you finish.

12. Rate the overall quality of the website

Mark only one oval.

	1	2	3	4	5	
Poor	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Excellent

2/19/2018

Revised Website Evaluation Survey

13. How easy are things to find on the website?*Mark only one oval.*

	1	2	3	4	5	
Hard	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Easy

14. How frustrating was it to use or navigate the website?*Mark only one oval.*

	1	2	3	4	5	
Extremely Frustrating	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Not Frustrating At All

15. Would you use this website as a resource?*Mark only one oval.*

	1	2	3	4	5	
Definitely No	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Definitely Yes

16. Any concluding feedback or suggestions you may have?

Powered by



Appendix G: 3D Printed Modeling Kit Cost Calculations

$$\begin{aligned}
 V &= \text{Part Volume (cubic in)} \\
 I &= \text{Part Infil (Percentage 0 – 1)} \\
 S &= \text{Support Material (Percentage 0 – 1)} \\
 Mc &= \text{Material Cost (\$/cubic in)}
 \end{aligned}$$

$$\text{Part Cost} = Mc * V * (I + S)$$

Equivalent Modeling Kit

Atom:

$$\begin{aligned}
 V &= 0.62 \text{ cubic in} \\
 I &= 100\% \\
 S &= 30\% \\
 Mc &= 0.47 \text{ \$/cubic in} \\
 \text{Part Cost} &= \$0.381
 \end{aligned}$$

Bond:

$$\begin{aligned}
 V &= 0.07 \text{ cubic in} \\
 I &= 100\% \\
 S &= 30\% \\
 Mc &= 0.47 \text{ \$/cubic in} \\
 \text{Part Cost} &= \$0.053
 \end{aligned}$$

1 Kit: 86 Atoms + 153 Bonds

$$\begin{aligned}
 86 * \$0.381 + 153 * \$0.053 &= \\
 \$32.68 + \$8.37 &= \$41.05
 \end{aligned}$$

Cost Effective Modeling Kit

Atom:

$$\begin{aligned}
 V &= 0.521 \text{ cubic in} \\
 I &= 40\% \\
 S &= 30\% \\
 Mc &= 0.47 \text{ \$/cubic in} \\
 \text{Part Cost} &= \$0.197
 \end{aligned}$$

Bond:

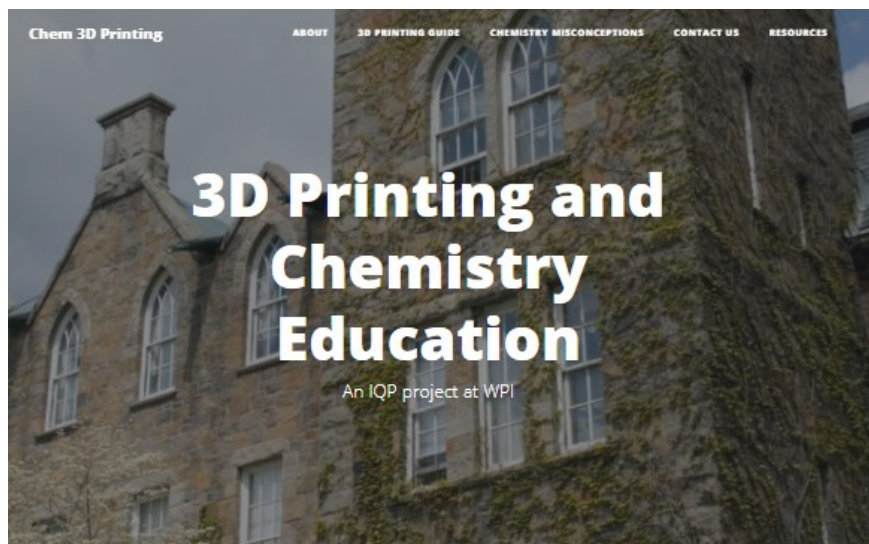
$$\begin{aligned}
 V &= 0.067 \text{ cubic in} \\
 I &= 100\% \\
 S &= 30\% \\
 Mc &= 0.47 \text{ \$/cubic in} \\
 \text{Part Cost} &= \$0.041
 \end{aligned}$$

1 Kit: 86 Atoms + 153 Bonds

$$\begin{aligned}
 86 * \$0.197 + 153 * \$0.041 &= \\
 \$17.07 + \$6.40 &= \$23.47
 \end{aligned}$$

Appendix H: Additional Website Images

Home



Start Here

Chemistry education can be tough without sufficient resources or models to complement teaching. That's why we are here to help you. With the use of 3D printing and our compendium of resources, you can find anything from lesson plans to 3D printable object files. You can dive right into the [Compendium of Resources](#) or you can answer a few questions below to get a [personalized guide](#).

On the navigation bar, you can find out a little more [About](#) us and the project we are working on. Have a 3D printer and don't know how to use it? Visit our simple [3D Printing Guide](#). You can also the [Search Resources](#) button to find chemistry related 3D printable objects and resources for the classroom, or personal use. We also have a list of [Chemistry Misconceptions](#) that includes ways to resolve common chemistry struggles. Have some feedback or questions? Don't be afraid to [Contact Us](#)!

Personalized Guide:



Do you know what 3D printing is?

YES

NO

Recent Information

3D Printing Resource Database

We started developing a 3D printing resource database for educators.

Chemistry Teacher Survey

We have a survey for chemistry teachers

we have a survey for chemistry teachers.

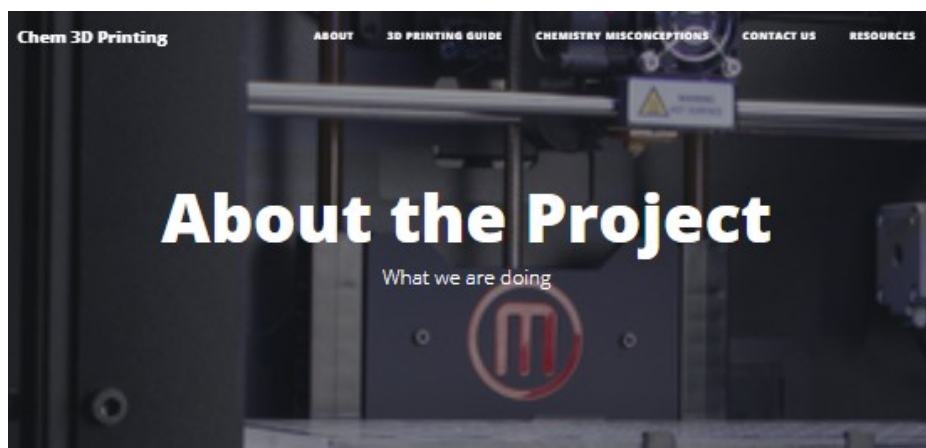
About the Project

The who, what and why.

How to Contact Us

We aren't impossible to reach.

About



The Why

Chemistry education is fraught with difficult concepts to teach. As a result many students have difficulty with chemistry as a subject. Our goal is to improve the students' understanding of chemistry topics.

The What

This website is an educational resource for teachers who are looking for new ways to combat common difficulty areas in chemistry. This website pulls together many different sources of 3D printing chemistry resources into one location so that finding helpful information is easier.

On the navigation bar at the top:

- [Chem 3D Printing](#): Go back to the home page of the website
- [About](#): (You are here)
- [3D Printing Guide](#): A quick and dirty guide to walk you through printing your first 3D object
- [Chemistry Misconceptions](#): A collection of common chemistry misconceptions and some resources (3D printable parts, simulations, etc.) that help address them
- [Search Resources](#): A compendium of resources we have collected to help with chemistry education. These resources include 3D part files, 3D printing services, additional 3D printing Guides, and some Lesson Plans

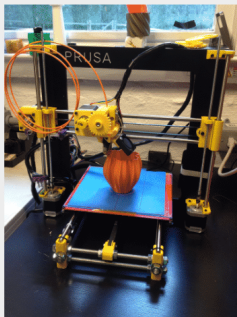
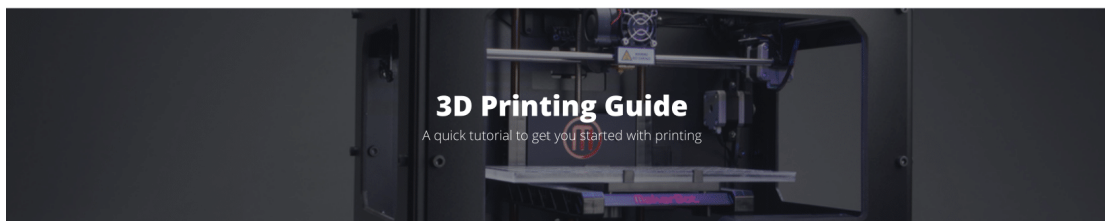
The Who

We are a group of students and faculty at Worcester Polytechnic Institute. For more information visit the [contact](#) page.

3D Printing Guide

Chem 3D Printing

ABOUT 3D PRINTING GUIDE CHEMISTRY MISCONCEPTIONS CONTACT US RESOURCES



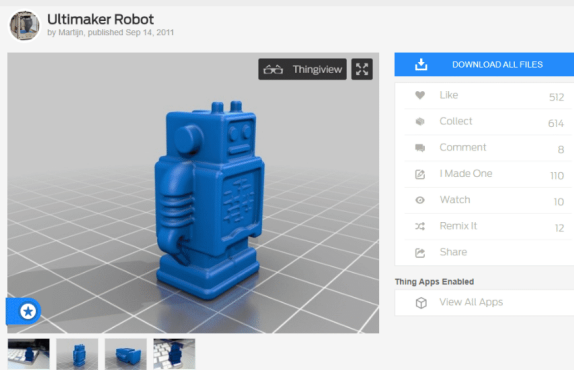
1. Setup. First, find a computer and download Cura from this website: [Cura Software](#). Follow the installation instructions for the software. A 3D printer is also required. Ask a friend or colleague who has one as they probably know how to use it.

There are three important pieces of information you must obtain before continuing: printer model, nozzle size, and material diameter.

The Printer Model name will typically be advertised on the printer or in the user manual.

Nozzle Size will be listed either on the side of the nozzle (the brass piece pointing downwards which extrudes plastic), or in the user manual.

Material Size will be typically listed on the side of the spool or can be measured with calipers.



2. Obtain 3D-printable object file. We have created a compendium of printable object files that are relevant to the physical sciences. This compendium can be found on the [database tab](#) at the top of the page.

For additional 3D printable objects, the easiest way to find a part file is by searching on databases of 3D printable part files. One of the most popular ones out there, which is free to use, is [Thingiverse](#). Using this website you can search a very large database for printable object files for free. We recommend using this robot by martijn for your first print: [Thingiverse Robot](#)

To download part file(s) from this website click the [DOWNLOAD ALL FILES](#) button to the right of the picture. This will then download the .stl file(s) that you can load into Cura.

Printers

Activate

Add

Remove

Rename

Prusa i3 MK2

Machine Settings: Connect Octoprint; Upgrade Firmware

Printer type: Prusa i3

Connection: The printer is not connected.

Machine Settings

Printer

Printer Settings

X (Width)

200

mm

Y (Depth)

200

mm

Z (Height)

200

mm

Build plate shape

Rectangular

☐ Origin at center

☒ Heated bed

Code flavor

Marlin

Printhead Settings

X min

20

mm

Y min

10

mm

X max

180

mm

Y max

180

mm

Gantry height

55

mm

Material diameter

1.75

mm

Nozzle size

0.4

mm

3. Set machine settings in Cura. First, open up Cura. It will prompt you to select which printer you will be using. Find yours or the one most similar to yours on the list. Click on the arrow in the top right corner and click add printer, then select yours from the list. Next, click the arrow again and click *Manage Printers*, followed by *Machine Settings*. Here, you will want to change the **Material diameter** and **Nozzle size** for your printer. Once finished, close out of those windows. The last change is to select which material you will be using on the top right. The material diameter and type is usually found on the roll of filament.

Print Setup

Recommended

Custom

Profile:

Fine 0.1mm

Search...

Quality

Shell

Infill

Material

Speed

Cooling

Support

Build Plate Adhesion

Special Modes

4. Set slicing settings in Cura. To start the editing process, first import your part by clicking *File -> Open File* and then select your file. Once the file is loaded in to Cura, click **Custom** on the upper right side of the screen. Follow the list below, clicking on the tabs indicated. Settings may vary with part size.

Quality: For large parts for which the estimated print time is on the order of hours, the print can be shortened by selecting a larger layer height (0.15-0.2 mm). For smaller parts with finer details, select a finer quality (0.06-0.10 mm). In general, larger layer height reduces print time, but also reduces print quality. We will use 0.1 mm for our robot.

Infill: If you think your part is going to require an appreciable amount of structural integrity, use 100% infill. Otherwise, 30% works great and will print much faster. We will use 30% for our robot.

Support: If your object has parts that overhang, like our robots arms or a bridge, use supports. Otherwise, do not. We will use supports for our robot.

Build Plate Adhesion: For parts with small amounts of material touching the base, use build plate adhesion. In general, always use build plate adhesion unless the part is very large. We will be using a brim for our robot.

Ultimaker Robot

by Martijn, published Sep 14, 2011

Download All Files

Like

512

Collect

612

Comment

8

I Made One

110

Watch

10

Remix It

12

Share

Thing Apps Enabled

View All Apps

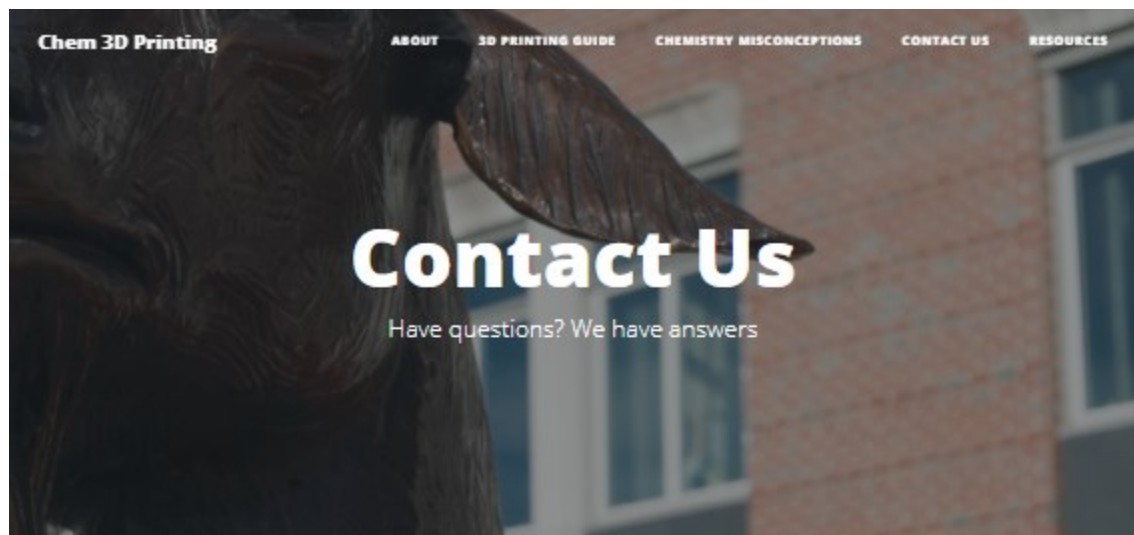
5. Print the part.

If you aren't printing the part, but rather having someone print the part for you, click the **Save to File** button on the bottom right of the screen. Once the file is saved. Give that file to the person who is printing the part along with the original .stl file(s) you downloaded.

If you are printing the part yourself, first, determine the type of digital media (e.g. SD Card, micro SD, USB drive) required for your 3D printer. Each 3D printer is different, so this section will require you to check your 3D printer's user manual. Once done slicing, you can insert your removable media to your computer and press the **Save to Removable Media** button on the bottom right of the screen. Then, plug in your removable media to the 3D printer. Next, navigate to the part on the printer's interface and click on it to start printing. It is advised that you stay near the printer while the first couple of layers are printed, since this is when errors usually occur. After that, your part should complete successfully! If the part starts off printing incorrectly, it is important to try to stop the print. Consult your user manual to figure out how to do so. If it does not complete successfully, consult your manual or search the web for your problem to find possible solutions.

Congratulations you've printed your first 3D part!

Contact Us



Who we are

We are a group of students and faculty and Worcester Polytechnic University. Contact us by clicking the email button at the bottom of the page or directly at chemiqp@wpi.edu.

Students

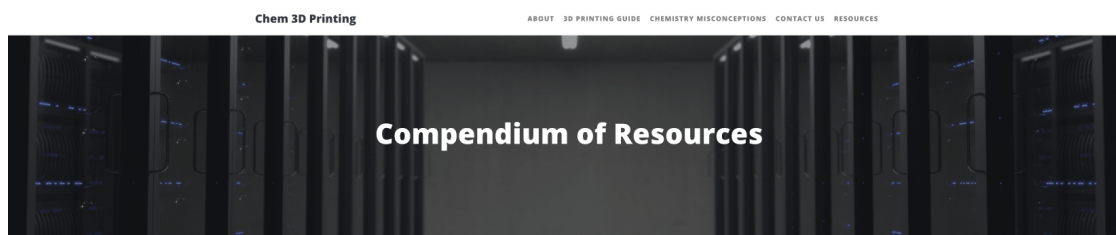
- John Stegeman (Junior at WPI)
- Dylan Muise (Junior at WPI)
- Joseph Calman (Junior at WPI)

Advisors

- Aaron Deskins (Associate Professor of Chemical Engineering)
- Amy Peterson (Assistant Professor of Chemical Engineering)

[SEND US AN EMAIL!](#)

Compendium of Resources




Chem 3D Printing

ABOUT 3D PRINTING GUIDE CHEMISTRY MISCONCEPTIONS CONTACT US RESOURCES

Compendium of Resources

3D PRINTED PARTS
RESOURCES
LESSON PLANS
3D PRINTING INTRODUCTION

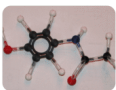
POTENTIAL ENERGY
IONIC BONDING
MOLECULAR STRUCTURE
NUCLEAR CHEMISTRY
PERIODIC TRENDS
BIOLOGY
ATOMIC ORBITALS
LAB EQUIPMENT
ORGANIC CHEMISTRY
ATOMIC STRUCTURE
ANATOMY



States of Water

By WPL_Chem3dPrint

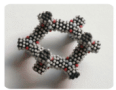
Recommended. This 3D printable tool helps address the common student misconception that molecules change size in different phases.



Molecular Model Set

By betawolf


This is a set of model atoms that can be connected together with flexible tubing to create molecular models. This print is for the molecular atoms, flexible plastic tubing must be bought separately. (3 mm internal diameter)



DMSE Molecule

By mecadense


An example of a crystalline unit cell molecule structure to print out.



Flexy-Frame Construction Kit

By Gyrobot


This model is designed to be printed with both flexible and rigid filament. It allows student to make molecules in 2D and then the flexible elements bend so they can transform the 2D molecule into 3D.



Hydronium

By NIH

3D Printable Model of a Hydronium (H₃O) Molecule.



Water

By NIH

3D Printable Model of a Water (H₂O) Molecule.



Ammonium

By NIH

3D Printable Model of an Ammonium (NH₃) Molecule.



Methanol

By NIH

3D Printable Model of a Methanol (CH₃OH) Molecule.



Formic Acid

By NIH

3D Printable Model of a Formic Acid (CH₂O₂) Molecule.



Methane

By NIH

3D Printable Model of a Methane (CH₄) Molecule.



CO₂

By NIH

3D Printable Model of a CO₂ Molecule.



List of Common Chemistry Misconceptions and Solutions

Chem 3D Printing

ABOUT 3D PRINTING GUIDE CHEMISTRY MISCONCEPTIONS CONTACT US RESOURCES

Common Student Struggles

Common Misconceptions

Below we have personally compiled a list of the most common misconceptions that chemistry students struggle with. Each section includes a list of these misconceptions, as well as a small guide on how to explain it. This may include the use of 3D printed tools, lesson plans, and online simulations.

Matter and its Interactions

(Click to Expand)

Students think molecules change size/shape with pressure or temperature changes
Students think identical molecules can vary in size
Students think molecules in different phases have different weights
Students think atomic radii depends solely on number of protons
Students think unbalanced chemical equations exist.
Students think when a reaction reaches equilibrium, the system stops reacting.
Description: Students don't understand the concept of equilibrium. Recommendation: Use simulations to help students visualize how reactions actually occur at the atomic level. <ul style="list-style-type: none"> • Reactions and Rates • Reversible Reactions
Students have trouble identifying what is oxidized and reduced in redox reactions.
Students think reactant and product concentrations are equal at equilibrium
Determining the effect of Le Chatelier's Principle on equilibrium
Students have trouble distinguishing between reaction rate and equilibria

Motion and Stability: Forces and Interactions

(Click to Expand)

Students think atoms only have 1 stable electron state
Students think ions in solutions are still connected
Students think there are only 2 types of bonding: ionic and covalent
Students don't understand the effect of different bond types (e.g. double, triple bonds) on shape
2D to 3D representation of molecules
Students have trouble identifying isomers
Students think isomers have different chemical formulas
Students don't understand how VSEPR predicts bond shape/angles
Students don't understand how a Lewis diagram relates to VSEPR

Energy

(Click to Expand)

Students think energy is required in both the forming and breaking of chemical bonds
Students think breaking bonds releases energy and forming bonds takes energy